A METHODOLOGY FOR ASSESSING IRRIGATION PRACTICE IN SMALL SCALE COMMUNITY GARDENING.

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ABSTRACT

The challenges facing small scale irrigation development in South Africa are varied and complex. This complexity is exacerbated by the many years of systematic neglect, in tandem with material and intellectual impoverishment of the majority of participants in this agricultural sector. Attempting to juggle sustainable development of small scale agriculture and environmental and socio-economic advancement is difficult, but there is sufficient evidence in the literature to suggest that small scale agriculture is increasing not only in South Africa but in Sub-Saharan Africa (Collier and Field, 1998)

There is no doubt that this observed increase in irrigated communal gardens result from their increasingly important role of providing food security and as means of augmenting family income. Hence the government, NGO's and other private sector organisations have increased their support for these small scale agricultural initiatives. Small scale agriculture is therefore increasingly becoming a common land use, and with this increased support, it is likely to become a major water user, particularly as it is located in close proximity to the water source. Hence both practices and processes for small scale agriculture require careful study.

Irrigation practices have been studied in KwaZulu-Natal where small scale community gardens are continuously developing. The study included two locations near Pietermaritzburg. The first, at Willowfontein, involved irrigation by furrow, and the second, at Taylors Halt, involved irrigation by hand, using containers. The dynamics of the subsurface flow was monitored using tensiometry and modelled in detail using a two dimensional, soil physics model, Hydrus-2D, to evaluate the application efficiency.

This study consisted of three parts viz: socio-economic system appraisal, technical measurement and monitoring, and modelling. Important findings obtained include the following:

▸ The highlighting of pertinent socio-economic issues governing water use and allocation and other operations in developing small scale agricultural conditions, including constraints to the development of this sector under the conditions described.

- The demonstration of the use of reasonably inexpensive, but sophisticated measuring techniques to observe the soil water processes in small scale community gardening practices.

- Accurate simulations of soil water infiltration, redistribution and uptake using the Hydrus-2D model. With these successful simulations, together with the results of the social system appraisal, more efficient irrigation scenarios are proposed and evaluated.
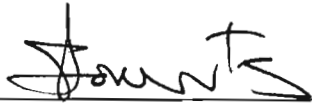
- The development of a methodology that could be used to assess small scale irrigation efficiencies, with computer simulation models used as tools to conduct such an assessment.

DECLARATION

I hereby certify that the research work reported in this thesis is the result of my own original investigation except where acknowledged.

Signed_____

Nhlanhla Sihlophe

Signed_____

Simon Lorentz (Supervisor)

their gardens.

Nick Walker for assisting me with some of the field work.

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LIST OF SYMBOLS AND ABBREVIATIONS

ACRU Agricultural Catchment Research Unit

AMIS Agency Managed Irrigation System

c   propagation velocity of electrical signal in vacuum or free space 3×10^8 m.s^{-1}

c_o specific water capacity   m^3.m^{-3}.m^{-1}

C_1 dimensionless constant in equation 1

C_2 dimensionless constant in equation 1

DMi   dry matter increment

DR   double ring infiltrometer test

E_p potential soil evaporation rate   mm.d^{-1}

ET_p potential evapotranspiration rate   mm.d^{-1}

FAO   Food and Agriculture Organisation

FMIS Farmer Managed Irrigation System

GWL(i) ground water level, usually negative or other time dependent prescribed   m
        boundary condition

h   capillary pressure head   m

        Capillary pressure is expressed in terms of a head of water, so:

        $h = (P_a - P_w)/(\rho g) = h_a - h_w$, where P_a is the non wetting phase pressure (normally air) and

        P_w is the wetting phase pressure (normally water), ρ is the density of water and g is the

        gravitational acceleration. Since, in an unsaturated porous medium, the air pressure head,

        h_a, is normally atmospheric and the pore water pressure head, h_w, is less than atmospheric,

        the value of h is a positive quantity. The capillary pressure head is therefore expressed as

        a positive quantity throughout this thesis and is synonymous with soil water tension ht

        ground water level, usually negative or other time dependent prescribed   m
        boundary condition

GREEN   Greater Edendale Environmental Network

hCritA(i)   Absolute value of the minimum allowed pressure head at the soil surface   m

hCritS   maximum allowed pressure head at the soil surface   m

INR   Institute of Natural Resources

K   hydraulic conductivity   mm.d^{-1}

K_a apparent dielectric constant of the soil

K_k unsaturated hydraulic conductivity similar to K(h)   mm.h^{-1}

$K_r(h)$	relative hydraulic conductivity	$mm.h^{-1}$
K_s	saturated hydraulic conductivity	$mm.h^{-1}$
$K(h)$	unsaturated hydraulic conductivity	$mm.h^{-1}$
L	length of the wave guide in TDR	mm
LDC's	Less developed countries	
L_t	width of the of the soil surface associated with the transpiration process	mm
L_x	width of the root zone	mm
m	dimensionless van Genuchten (1980) soil water hydraulic parameter	
α	dimensionless van Genuchten (19800 soil water hydraulic parameter	mm^{-1}
CPH	capillary pressure head	m
n	dimensionless parameter in the soil water retention function	
NEWSWB	New Soil Water Balance (Model)	
NT	No tillage	
OTD	Observed tensiometer data	
PDP	Portable Dielectric Probe	
PO	value of the pore water pressure pressure head h_{w1} (Figure 15), below which roots start to extract water from the soil	m
PO_{pt}	value of the pore water pressure head h_{w2} (Figure 15), below which roots start to extract water at the maximum possible rate	m
Prec(i)	precipitation	$mm.d^{-1}$
P2H	value of the limiting head h_{w3} (Figure 15), below which roots cannot extract water at a maximum rate (assuming potential transpiration rate of r2H)	m
P2L	value of the limiting pore water pressure head h_{w3} (Figure 15), below which roots cannot extract water at a maximum rate (assuming potential transpiration rate of r2L)	m
P3	value of the pore water pressure head h_{w4} (Figure 15), below which root water uptake ceases (usually equal to the wilting point)	m
PRA	Participatory Rural Appraisal	
PT	Plough Tillage	
Q_a	parameter in the soil water retention function in Hydrus model	$m.m^{-1}$
Q_k	volumetric soil water content corresponding to K_k in Hydrus model	$m.m^{-1}$

Q_m	parameter in the soil water retention function in Hydrus model	mm^{-1}
Q_r	residual soil water content in Hydrus model	$m^3.m^{-3}$
Q_s	saturated soil water content in Hydrus model	$m^3.m^{-3}$
RAM	Readily available moisture	
RDP	Reconstruction and Development Programme	
rGWL(i)	drainage flux across the bottom boundary	$m.m.d^{-1}$
RRA	Rapid Rural Appraisal	
rRoot(i)	potential transpiration rate in absolute value	$m.m.d^{-1}$
rSoil(i)	potential evaporation rate in absolute value	$m.m.d^{-1}$
r2H	potential transpiration set set at 5	$m.m.d^{-1}$
r2L	potential transpiration rate set at 1	$m.m.d^{-1}$
s	water uptake by roots	$m.m^{-1}.d^{-1}$
Se	dimensionless effective water content	
S_{max}	maximum root water uptake rate	$m.m^{-1}.d^{-1}$
SCS	Soil Conservation Service	
SSIS	Small scale irrigation systems	
SWACROP	Soil Water, Actual transpiration and CROp Production (Model)	
SWB	Soil Water Balance (Model)	
SWIM	Soil Water Infiltration and Movement (Model)	
t	time	s, min or d
tAtm(i)	time for the ith data	s, min or d
TDR	Time Domain Reflectometry	
T_p	potential transpiration rate	$mm.d^{-1}$
V	propagation velocity	$mm.s^{-1}$
VIRP	Village Irrigation Rehabilitation Programme	
z	vertical co-ordinate	m
Z	effective rooting depth	m
ρ_b	bulk density	$kg.m^{-3}$
φ	porosity	$m^3.m^{-3}$
$\alpha(h)$	reduction factor	
θ_r	residual water content	$m^3.m^{-3}$
θ_s	saturated water content	$m^3.m^{-3}$

θ volumetric soil water content $m^3.m^{-3}$

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1. INTRODUCTION

The challenges facing small scale irrigation development in South Africa are varied and complex. This complexity is exacerbated by the many years of systematic neglect, in tandem with material and intellectual impoverishment of the majority of participants in this agricultural sector. Attempting to juggle sustainable development of small scale agriculture, environmental and socio-economic advancement is difficult, but there is sufficient evidence in the literature to suggest that small scale irrigation is on the increase in Africa.

"Small irrigated vegetable plots, grouped into communal village gardens and supplied with water from a hand pumped well are of increasing interest to Africa, especially to women" (Collier and Field, 1998).

Contributing to this increase in small scale irrigation projects in South Africa, is the high rate of unemployment. It is therefore, seen by the vast majority of the unemployed to be vitally critical in playing a central role towards the reduction of poverty. This is equally true for the ailing impoverished masses in Sub-Saharan Africa, and in response to this increase in demand for irrigation projects, the new South African government has increased funds for the development of irrigated community vegetable gardens. This is an initiative consistent with the aims of the reconstruction and development program (RDP). The local office of the Department of Agriculture identifies deserving community gardening projects in its area. Funds are then provided for purchasing and setting up the irrigation infrastructure. Whilst this undertaking is seen to be a positive step on the part of the government, there is a need to exercise caution so as to avoid making or repeating the mistakes of the past.

Many irrigation projects that were established by the previous government in the former Bantustans, failed to produce to predicted levels. This was mainly because the past government of South Africa favoured a top - down approach which disregarded participation by the target beneficiaries during the planning and subsequent stages of the project. Van Averbeke, Belete, Igodan and Marete (1998) state that South Africa has a long way to go in removing the damage that has been inflicted as a result of development policies and programmes which did not recognise the need for consultation and community participation. Bembridge (1996) concurs and add that, this happened despite the demonstration by local research of the need for a change in

planning and development of irrigation schemes in South Africa, recommending participation of farmers in planning and the decision making processes.

In these irrigation projects the mis-match between the organisational basis surrounding water use and allocation and irrigation infrastructural development is indicative of the statement by van Averbeke, Belete, Igodan and Marete (1998). Several other authors have also highlighted this problem. A study conducted by de Lange (1994), identified the following as some of the problems faced by small scale farmers in South Africa:

▸   lack of water supply for irrigation purposes,

▸   lack of assured water supply,

▸   shortage of water supply technology,

▸   lack of technical support,

▸   lack of guidance, and

▸   inefficient and ineffective management styles.

De Lange (1994) also revealed the need to investigate actual crop water use to enable recommendations to be made to small scale irrigators, since the results of field evaluations, combined with information from the farmers, suggested that less irrigation water was applied than is generally recommended for maximum crop yields.

Since irrigated community gardening has offered renewed hope to the unemployed in South Africa in terms of providing food security and in serving as a means of augmenting family income, it is imperative that solutions are found to the problems facing small scale irrigation development.

With increasing government support in South Africa, small scale agriculture is likely to become a major water user, particularly as they are located in close proximity to the water source. Hence, both practices and processes of small scale agriculture require careful study.

Irrigation practices have been studied in KwaZulu-Natal where small scale community gardens are rapidly developing and have the potential of becoming a major water user. The study includes two locations. The first, at Willowfontein near Pietermaritzburg involves irrigation by furrow, and the second, at Taylors Halt, involves irrigation by hand using containers. The dynamics of subsurface flow is monitored and modelled in detail to assess and advise upon

application efficiency.

The work presented in this study addresses the need for an evaluation of small scale irrigation practices, processes (i.e. mechanisms of water infiltration and distribution resulting from practices specific to small scale irrigation) and efficiencies. The objectives of the study included a social and technical system appraisal as these two are directly linked.

(a)   Social system appraisal:

▶   To establish the social perceptions of water use and whether, under the conditions researched, there were any existing rules of water allocation and distribution,

▶   To establish the organisational basis surrounding those existing rules of water allocation and distribution and

▶   To illuminate other social issues pertinent to small scale irrigation development.

(b)   Technical system analysis:

▶   To test and determine whether instrumentation could be used to monitor and understand soil water dynamics under developing small scale agricultural conditions and

▶   To use existing modelling tools to simulate processes in small scale irrigated agriculture with a view to devising protocols for efficient irrigation practices.

It is critical to understand the current state of small scale irrigation in South Africa and elsewhere, so as to identify common problems and approaches used in solving those problems. On the basis of this background a comprehensive literature review on small scale irrigation has been carried out in the following chapter. Methodologies that have been used elsewhere under similar conditions to gather information / data on social issues are also reviewed. A brief review of soil moisture measurement and monitoring techniques applicable to small scale irrigation also forms part of this chapter. Those techniques that would be most appropriate for use in developing conditions are highlighted. Chapter 2, is then concluded with a review of different soil water balance models. Again, particular reference is drawn to those models that would be most suitable for simulating localised soil water dynamics under small scale agricultural conditions.

Chapter 3, covers the methodology used to gather and / or monitor data on the social aspects of this study, the soil moisture measurement and monitoring techniques employed, and finally the modelling approach used to test the efficiency of known strategies and / or develop alternative irrigation strategies.

This study comprises three parts viz: social system appraisal, technical system analysis (instrumentation and monitoring) and modelling. The results and analysis presented in Chapter 4, follow the same order. The technical data analysed in this chapter are tabled in appendices. All the measured and simulated results are discussed both during the presentation in Chapter 4 and in more general terms in Chapter 5, with concise conclusions. Since this research was the first of its kind to combine two different aspects, i.e. social issues and physically based scientific processes within the scope of small scale irrigation, a number of lessons have been learnt, since its inception. These lessons have been summarised in Chapter 6 and form recommendations for future research and recommendations for successful operation of community gardens.

2. LITERATURE REVIEW

2.1 Introduction

This chapter is a literature review on the main aspects of this research work, which includes: small scale irrigation systems in the developing world; rural and participatory methodologies; soil water measurement and monitoring techniques and soil water balance modelling in irrigation.

A review of small scale irrigation systems is essential in order to gain an understanding of the state of the-art in small scale irrigation, beyond the situation local to the research sites. This is critical for the identification of common experiences, and problems, and solutions that have been used elsewhere to solve specific problems. Hence, this review forms the basis for this current study. Research carried out in this study also involved addressing social issues pertinent to water use and allocation, with respect to small scale irrigation. Hence, a literature review of participatory methodologies that have been used successfully elsewhere was critical as such methodologies had to be adopted for use in the study. Soil water measurement and monitoring techniques, including soil water balance models have been used extensively for many decades in the developed world. However, these techniques and models have not been used extensively in developing rural conditions. Identification of robust and appropriate techniques and models to use in this study, required that these techniques and models be reviewed with the aim of highlighting those that are suitable.

2.2 Small Scale Irrigation Systems (SSIS)

During the past decade in Asia and in many less developed countries (LDCs), the focus of irrigation development has been shifted from a strategy that emphasises constructing large scale irrigation systems to the one that helps existing small scale irrigation systems to improve their importance. Phillips-Howard and Porter (1996) state that larger scale schemes have been substantially discredited across Africa, but that small scale irrigation is seen as a promising means to raise both agricultural productivity and employment. It comprises half of Africa's irrigated area and is expanding rapidly, even where there is little government support. There are, as far as could be ascertained from a survey approximately 202 small scale farmer schemes in South Africa. These comprise approximately 47 486 ha of land under small scale irrigation

(Bembridge, 1997). In South Africa, according to de Lange (1994), the small scale irrigators can be categorised in terms of their irrigation water supply as follows:

(a) farmers on an irrigation system (communal water supply infrastructure);

(b) vegetable gardeners (communal water supply infrastructure) and

(c) independent farmers (each with a private water supply).

For the purpose of this study, small scale irrigation could mean either of the three above-mentioned categories, since in South Africa discussions are as yet incomplete on the definition of what constitutes a small scale farmer, a subsistence farmer and a smallholder irrigator. Vincent's (1994) disapproval of size as a way of defining small scale irrigation stems from the fact that size seems to give the idea that small scale irrigation can be developed through a scaled down version of standard irrigation design approaches. He adds that while under 100 ha would be criterion for small scale irrigation in Africa, under 200 ha is the criterion for minor irrigation in India.

One of the distinctive characteristics of small scale irrigation systems is that, predominantly, they are gravity systems rather than pressurised systems, based on the hydraulic principle that determines system design (Vincent, 1994). This explains the uncertain and unequal development of SSIS in many countries, since large scale systems require sophisticated 'technology' to be financially or scientifically attractive and these technologies are beyond the financial and operating capabilities of small scale farmers. Hence, it is important to differentiate participants in small scale irrigation so as to identify problems they experience and solutions thereof. The following section explores womens' role in small scale irrigation and the problems they face which in turn constrain small scale irrigation development.

2.2.1 Womens' role in smallholder irrigation

There seems to be general agreement that mainstream small scale irrigation development is predominantly a women issue, and that the general lack of capacity of women has to be addressed in order to achieve sustainable development of rural agriculture. Present estimates of the contribution of women to smallholder irrigation in Africa are in the range of 60% to 95% of the total work required (Chancellor, 1996 cited in Chancellor, 1997). In South Africa it is estimated that at least 150 000 growers participate in community gardening projects. Most of the participants in these gardening projects are women (de Lange, 1994). Available data on characteristics of small scale farmers on irrigation schemes in various parts of South Africa also

show that 10-20 % were widows, and in the majority of food plots and community garden schemes about 90% of participants were women (Bembridge, 1996 cited in Bembridge, 1997).

Over the years there has been a steady increase in the number of women participating in agricultural activities. The intensification of agriculture which accompanies irrigation development requires more labour input per unit area of land, and this has been the cause of the increase in the number of woman participants in the small scale agricultural sector. Increasingly women provide the labour, partly to perform tasks traditionally allocated to them such as weeding and transplanting but also to fulfill the role of growers of food, complementing the male role of providing meat (Chancellor, 1997).

Although women are highly involved in many agricultural activities including irrigation, they lack skills and capacities to participate effectively in operating, managing and developing systems to meet their needs. Evidence of this fact is the common technical mistake in many community gardens of an incorrectly sited reservoir, resulting in inadequate pressure and long term frustration of users (de Lange, 1994). Guijt and Thompson (1994) suggest that acknowledging the womens' substantial role in agricultural production and therefore the need to draw them in as irrigators, could greatly improve the performance of the irrigation sector.

For a speedy development of the small scale irrigation sector it is important to identify most, if not all, of the constraints and opportunities. The following section explores key constrains and opportunities in small scale irrigation.

2.2.2 Constraints and opportunities

Bembridge (1990) cited in Bembridge (1997) states categorically that the major constraint throughout most of the small scale farmer irrigation projects is the lack of strong local organisation and leadership. Participants in small scale irrigation tend to resist bureaucracy which does not allow for individuality in decision making. This then leads to a multitude of problems which affect the sustainability of small scale irrigation systems. The other constraints as identified by the farmers in the Eastern Cape (former Transkei) have been shortages of capital, extension and infrastructure available for small farmer projects as well as land pressure. In addition to the above-mentioned constraints, women irrigators are further disadvantaged by the lack of easy access to farm inputs, new technology or other services to improve their

livelihood (Bembridge, 1997).

Since women play an important role in small scale irrigation, it is therefore essential to ensure that women participation does not decrease. This could be done through the adoption of strategies which reduce constraints specific to women (Chancellor, 1997). These strategies would involve adequate funding for participation where the principle of gender equality has been accepted. Cheap and quick participatory methods which allow continued exclusion of women, or at best, made it hard for them to participate fully, should be done away with. Women should be alerted to opportunities and pitfalls that can arise and should be encouraged to use the opportunities provided for them to participate in a turnover process such as the turnovers of existing government run or assisted smallholder schemes to private individuals. In designing new irrigation systems, community involvement at the earliest stage is required and participation should be planned to ensure that women are included and empowered.

On the Jos plateau in Nigeria, a highly productive and profitable round the year system of small basin irrigation has evolved in response to the high and growing demand for vegetables. Since the labour requirement is about 10 persons/ha, this system provides many jobs in rural areas where other opportunities are few. According to Phillips-Howard and Porter (1996), if only 5% of the estimated maximum irrigable area of Eastern Cape were brought under such a system, then about 400 000 jobs could be created directly, plus many others in transport, marketing, processing and services. This confirms the popular view that sustainable development of smallholder irrigation would bring about numerous economic benefits to the developing countries. These benefits would be heavily reliant on effective management on the part of the farmers. It is therefore crucial to examine the management options that are available for the development of the small scale irrigator.

2.2.3 Management of irrigation schemes

A number of researchers on the subject of large scale irrigation in developing countries seem to agree that central to the failure of these schemes is the lack of the following:

(a) necessary management skills,

(b) technical support,

(c) adequate extension services,

(d) commitment, involvement and a sense of ownership on the part of the farmers.

Another contributing factor to failure is said to be the incompatibility between the engineering infrastructure, modern irrigation technologies and the local socio-economic environment. Studies conducted have shown that management of irrigation schemes by an outside agency serve as a disincentive to farmers. This causes the farmers to lose the sense of ownership of the scheme and consequently commitment and involvement the scheme. The World Bank in 1994 reported that large scale irrigation systems continue to be among the infrastructure projects that have the lowest levels of performance in the developing world (Lam, 1996).

The suggestion by a number of authors on the subject of SSIS that traditional top-down externally managed systems are unacceptable to the farmers has been corroborated by de Lange (1994). She states that in South Africa, irrigation schemes where farmers on schemes have decision making power and freedom of choice in regard to crop selection, irrigation and production practices and marketing have produced a high degree of personal satisfaction and a sense of belonging. She adds that these schemes do not rate highly in regard to technical aspects due to a lack of adequate support and advisory services, something which she recommends should be corrected by the State.

In Nepal rehabilitation of existing small scale irrigation schemes was conducted. After the rehabilitation process they found that these schemes performed poorly, worse than they did prior to the rehabilitation process. The reasons that were identified as the cause of poor performance after the rehabilitation process were:

- engineering infrastructure to fit the local socio-economic environment was inappropriately constructed,
- engineering infrastructure was of sophisticated design and was therefore difficult to operate and maintain, and
- inadequate understanding and knowledge of modern technologies used in agricultural planning and management.

It was after the abovementioned experience in Nepal that the Nepalese government conducted a study which compared two management systems, i.e. Agency Managed Irrigation System (AMIS) and Farmer Managed Irrigation System (FMIS). Careful studies revealed that irrigation officials in AMIS formulated and enforced rules for water allocation. These rules were designed solely upon the premise of easy implementation and were therefore less flexible and less

compatible with the local situation. The farmers did not obey these rules if they perceived the chances of changing the rules to be slim, or if they thought that complying with the rules meant limiting their crop yield.

The strength of farmer managed irrigation systems is that farmers can engage in rule crafting activities day by day (Lam, 1996). In addition, rules that are made by farmers are likely to take information and knowledge about the local situation into consideration, and rules that are designed with close reference to the problem that they are intended to solve are likely to be more effective than those designed at some distance (Lam, 1996). Analysis of the effect of governance structure in Nepal appeared to suggest that a farmer managed governance structure performs better than an agency managed one. However, caution is warranted before drawing such a conclusion (Lam, 1996). It is more useful to understand the underlying principles and mechanisms of institutional design that provide positive incentives to farmers and officials to work with one another. To recognise that there are diverse ways of putting institutional arrangements together, to complement the physical and socio-cultural attributes of a particular situation, hence, to attain productive patterns of relationships, is a prerequisite for successful intervention (Lam, 1996).

Amongst other suggestions made by de Lange (1994) on small scale irrigation development in South Africa, is the suggestion to rehabilitate the already existing small scale irrigation schemes. Many of these schemes are non-operational for a variety of reasons. Past policies of this country have been linked to the current state of these irrigation schemes. To avoid repeating or making any more mistakes the rehabilitation process in South Africa would have to be infused by experiences from other countries with similar socio-economic backgrounds. In line with this sentiment, the next section examines the reasons behind the failures of a comprehensive Village Irrigation Rehabilitation Programme (VIRP) that was carried out Sri Lanka. These failures were reported in two areas where the VIRP was introduced, that is in Ambewila and Thambagamuwa.

2.2.4 Rehabilitation of small scale irrigation systems (The Sri-Lankan Experience)[1]

In the mid 1980's the government of Sri Lanka decided to turn to a strategy based on the intensification of agricultural production on existing irrigated lands, especially those coming

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[1] This section is based on case studies conducted by Abeyratne (1990)

under minor irrigation tanks (reservoirs) and anicuts (weirs). Within this large effort, the VIRP was the first comprehensive program to look into all aspects of improved water management under small scale systems. This program proposed to rehabilitate over 1200 village tanks (reservoirs) and anicuts (weirs) in 14 districts of the island.

The broad objectives of the VIRP were the following:

▸ physical rehabilitation of deteriorated minor irrigation schemes to increase agricultural production and farm incomes,

▸ the introduction of a systematic water management programme to ensure efficient use of water once rehabilitation work was completed.

It was also believed that rehabilitation of small scale tanks and anicuts would offer the following advantage:

▸ short planning and implementation periods compared to rehabilitation of large scale irrigation works,

▸ dispersion of government funds to neglected rural areas for the upliftment of the welfare of the poorest sections,

▸ creation of conditions for efficient use and control of water, and as a consequence, expansion of the cropped area as well as of cropping intensity.

Historically, village tanks were taken to be items of government intervention because of their sophisticated physical structures which needed to be kept in working order, and because tanks were also considered to be hydraulically interdependent. In rehabilitating these tanks, the government was particularly concerned about breaches that could result in the loss of life and property under village tanks further downstream. The socio-ecological context was such that tank villagers tended to be relatively cohesive communities ordered around the tank water source. In turn the village tank provided an economic livelihood, and social status and identity to the villagers.

Anicuts on the other hand, were usually temporary structures, constructed with large boulders plugged with mud and straw. When floods eroded away the weirs, local effort was expended to replace them, and the government saw little need to intervene. Another factor that contributed to the governments reluctance to rehabilitate anicuts was that in places where anicuts predominated, land tenancy structures were highly exerting on tenants farming the land and gave little motivation to invest extra ordinary efforts on system maintenance. It was the introduction

of the Paddy Lands act in 1958 that relieved many of the tenancy problems, and that entrusted the Department of Agrarian Services to look into anicut refurbishment. The main purpose of rehabilitation was to prevent the need for the seasonal replacement of the eroded weir, rarely was it aimed at augmenting water supply.

In this thesis reference is made to two case studies of the VIRP in Sri-Lanka. One in Ambewila and the other in Thambagamuwa.

Ambewila comprised of three areas that made up the irrigation villages. These were Uda and Pahala Panthiya and Dingiriwelyaya. Prior to the implementation of the VIRP, 27 ha of Uda and Pahala Panthiya were cultivated in alternate years during the Maha (wet) season. During this time Dingiriwelyaya also cultivated with drainage water that allowed only 24 ha of the area to be irrigated. After the refurbishment of the tank in Ambewila it was possible to irrigate Uda and Pahala Panthiya in alternate seasons and the rest of Dingiriwelyaya could be irrigated with drainage water. A rotational system was instituted by the department of agrarian services after Dingiriwelyaya registered as rice land for purposes of acreage tax. The institution of this rotational system meant that Dingiriwelyaya had official rights to the tank water supply, and had to cultivate in the Yala (dry) season together with Uda Panthiya, Pahala Panthiya was to cultivate during the Maha season. On the understanding that it would be impossible to cultivate all three tracts together, farmers in collaboration with the Department of Agrarian Services agreed on the rotational system.

The VIRP implementation in Ambewila raised expectations among villagers that with refurbishment, the water supply was to be significantly increased such that all three tracts could be cultivated in both seasons without problems. Although water supply was increased, villagers were only able to cultivate the three tracts for a short while. This was largely because with time the tanks became silted as well as that encroachment in the upper reaches made additional demands on the available water supply. It became evident that it was not possible to irrigate all three tracts in both seasons. Hence, the battle over rights to irrigate from the tank started between the Panthiya and the Dingiriwelyaya villagers. The Uda and Pahala Panthiya villagers based their claim to superior rights to the tank water supply on that the tank resided on the Uda and Pahala Panthiya lands. On the other hand the Dingiriwelyaya villagers based their claim for rights to the tank water supply on the basis of that their lands were registered rice lands, and as

such had rights to the tank water supply.

The battle for rights continued for a long period with the Uda Pahala Panthiya villagers enjoying political support, as some of the politicians owned rice tracts in Uda Panthiya. While the battle went on, the system continued to be in disarray with Uda and Pahala Panthiya cultivating both seasons and the Dingiriwelyaya attempting to do the same without success. During this time agricultural production in Dingiriwelyaya reached very low levels as a result of not having a successful cultivation season for several seasons. This raised emotions to the extent that Dingiriwelyaya farmers engaged in ad hoc individual attempts to disrupt water supply to the other tracts. Tensions became high in the system such that ultimately, intervention resolved that they revert to the old alternate irrigation system where both Uda Panthiya and Dingiriwelyaya irrigate in Yala. This agreement was reached so as to ensure minimum subsistence for all cultivators.

In Thambagamuwa, there was an elaborate form of rotational tenure, where people land and water were rotated. This rotational system was a mechanism used by the owners of rice land to land subdivision through inheritance, and the water rotation worked smoothly with every effort made to stick to the cultivation schedule and not to spillover to the alternate tracts season. Similarly, though highly elaborate, the different forms of rotational tenure bound the community together and spread each cultivators risks and interests widely. Most importantly, it served to equalize access to the critical resource. It was unfortunate that the rehabilitation programme presented them with new and unfamiliar challenges.

In Thambagamuwa, the VIRP implementation took a blueprint approach with contractors installing the same diameter-outlet pipes for all irrigated lands irrespective of the size of the land. Farmers' suggestions of modifications to the installation plan were completely ignored. When some farmers protested that areas less than their own were receiving the same amount of water as their own, they were told that the irrigation department had only 10 cm outlet pipes in stock. The fact that all pipe outlets had a uniform diameter irrespective of the area they had to irrigate caused even more acrimony among the farmers whose land suffered most. Eventually these farmers decided to alter the system of water supply and re-direct water into the field as they had before the rehabilitation programme.

The fact that the programme of rehabilitation took a blueprint approach in Thambagamuwa confirms the notion that small scale irrigation systems fall within the sphere of the state's responsibility. The system was selected on criteria determined by national policy and recommended by the member of parliament of the area. Rehabilitation work was carried out by the government departments amongst themselves. The whole process was merely a "taking over and a handing over" exercise between two government departments. Existing patterns of water management and water distribution were simply overlooked, and structures determined and placed to match the estimated value of the contract. Farmers were not sufficiently organised nor motivated as a group to attempt to counter this. The farmers did not have the slightest idea of the roles they could have played in the rehabilitation process, they assumed that it was the responsibility of the government to finance and undertake rehabilitation work. Farmers had no idea that they should or could obtain the contract as a group and undertake rehabilitation work themselves. Similarly they had neither expectations about nor a say in the quality of the construction. This is not because they were afraid to confront the Irrigation Department personnel, it was simply because they believed that it was not within their scope of operation. These are lessons South Africa can learn from the Sri-Lankan experience, especially in the light of the many small scale irrigation schemes that are dysfunctional, awaiting rehabilitation to be instituted by the government.

Since this project involved interacting with the communities in each of the research sites, it was therefore necessary to conduct a literature review on rural appraisal methodologies that have been used elsewhere under similar socio - economic conditions. This was to enable the adoption of data gathering methodologies most suitable for conditions studied in this project.

2.3   Methods of Data Collection in Rural Situations in Developing Countries

In the past methods of data collection in rural situations often favoured a top down approach. In recent years the emphasis has been placed on participatory methodologies. The following two sections explore these two types of approaches.

2.3.1   Conventional methods of data collection.

Until recently, conventional methods of rural development analysis were characterised by the following:

- ▸ long duration of data collection,

- ▸ fixed and formal structure,

- ▸ limited scope usually concerned with a single development issue and in practice ignoring wider interlinkages and implications,

- ▸ weak integration even if a multidisciplinary team was involved,

- ▸ top down direction,

- ▸ poor level of participation between local farmers/people, researchers or decision makers,

- ▸ and exorbitantly high costs and inefficiency in time and manpower.

According to Conway, McCracken and Pretty (1988), conventional techniques often included statistical economic analysis, detailed vegetation and soil surveys using standardised questionnaires. Conway *et al.* (1998) state that, since they were characteristically inflexible, insensitive to local conditions and since they lacked breadth or integration, the recommendations so produced were often inappropriate and out of date.

In order to address this concern there has in recent years been a concerted move towards the development of a more participatory style of development (Nabasa, Rutwara, Walker and Were, 1995). This type of approach requires the active involvement and participation of the people being targeted. This approach has involved the further development of different techniques of information gathering known collectively as methods of rapid rural appraisal (RRA), into techniques which involve the active participation of rural communities, i.e PRA techniques.

2.3.2 Description of rapid rural appraisal (RRA) and participatory rural appraisal (PRA) techniques.

Chambers (1992), describes rapid rural appraisal (RRA) as a form of data collection by outsiders who then take it away and analyse it. RRA is intended for learning by outsiders. Participatory rural appraisal is more participatory, meaning that outsiders are convenors, catalysts and facilitators to enable people to undertake and share their own investigation and analysis (Chambers, 1992). It is intended to enable local people to conduct their own analysis, and often to plan and take action.

The main techniques used in PRA are the same as are used in RRA but with more emphasis in local participation and feedback. These techniques include direct observations, which is another

way an outsider can learn about an area. Secondary sources include semi-structured interviews, key informants, participatory mapping and modelling. Other secondary sources are transect walks, Venn diagrams, time lines and trend change analysis, oral histories and life histories. These may be supplemented with seasonal calenders, daily time use, livelihood analysis, matrix scoring and ranking, scoring and case studies, team contracts and interaction, and presentation and analysis.

2.3.3 Pros and Cons of participation.

Clayton, Oakley and Pratt (1997) mention the following as some of the pros and cons of participation in development activities.

Arguments for participation are the following:

- participation helps to build local capacities. It also helps to secure the sustainability of the activities as the beneficiaries assume ownership and are willing to maintain its momentum,

- participation can often help to improve the status of women by providing the opportunity for them to play a part in development work,

- participation can lead to better targeting of benefits to the poorest and can increase the efficiency of development activities in that, by involving local resources and skills, it can make more efficient use of expensive external costs, and

- people's participation can increase the effectiveness of development activities by ensuring that they are based upon local knowledge and understanding of problems and will therefore be more relevant to local needs.

Arguments against participation are the following:

- participation costs time and money, it is essentially a process with no guaranteed impact upon the end product,

- participation can be a destabilising force in that it can unbalance existing socio - political relationships and threaten the continuity of development work,

- processes of participation are irrelevant and a luxury in situations of poverty and it will be difficult to justify expenditure on such a process where people need to be fed and their livelihood secured, and finally

- participation is often driven by ideological fervour and is less concerned with seeking to

secure direct benefits for people from development activities than with promoting an ideological perspective into development.

The study carried out at Willowfontein and Taylors Halt, KwaZulu-Natal, South Africa, was planned to include instrumentation, with the intention of monitoring soil water movement within the soil profile, as well as measuring the meteorological variables such as rainfall. This was done to get an idea of how well the system was managed. It was therefore essential to review monitoring techniques that have been used elsewhere, with a view of identifying those suitable for adoption for the purposes of this study. The various soil moisture measurement and monitoring techniques are described in the following section.

2.4 Soil Water Measurement and Monitoring Techniques

Accurate measurement of soil moisture is a common requirement of field based hydrological or ecological research (Chanasyk and Naeth, 1996), and the capability to monitor soil water status and record changes in time and space are important for adequate validation of modelling of soil water dynamics. Topp, Watt and Hayhoe (1996) state that, in addition to applications in modelling, the measurement of water content in space and time is important for monitoring the hydrological water balance, measuring agricultural or forest water use efficiency, or monitoring changes in water content for irrigation scheduling. Topp *et al.* (1996) also maintain that, the effective use of water content values for many uses such as irrigation scheduling depends on rapid and reproducible recovery of data from a number of representative locations. Since the methods of measuring soil water content and soil water potential continue to evolve and improve, it becomes essential to understand which measuring techniques to use, under which conditions and for what purpose. The following measuring techniques are reviewed in the subsequent sections:

- ▸ gravimetric method with oven drying,
- ▸ neutron moisture meter,
- ▸ high frequency electrical techniques (capacitance, portable dielectric probes (PDP) and time domain reflectometry (TDR)),
- ▸ and tensiometry

2.4.1 Gravimetric method with oven drying

This method involves collecting and weighing a moist sample, oven drying it at 105°C to achieve a constant mass, reweighing it and calculating the mass of water lost in relation to the mass of the dried soil (Topp *et al.*, 1996). According to Topp *et al.*, (1996), this is the most universally accepted and widely used method of measuring soil water content.

Advantages of the gravimetric method

- it is simple to use,
- reliable measurements of soil moisture can be obtained and
- tools and equipments are cheap

Disadvantages of the gravimetric method

- removal of samples destroy the site of measurement,
- for validation or testing field scale or other area models, the gravimetric method becomes a costly choice and usually the sampling frequency limits severely the amount of data that can be collected for a given purpose (Topp *et al.*, 1996).

2.4.2 Neutron moisture meter

The underlying principle of neutron probe operation as discussed by Chanasyk and Naeth (1996) follows. Neutrons with high energy are emitted by a radioactive source into the soil and are slowed by elastic collisions with nuclei of atoms, a process called thermalization. The average energy loss is much greater with neutrons colliding with atoms of low atomic weight, than from collisions with heavier atoms. In soils the low atomic weight atoms are primarily hydrogen and, as a result, hydrogen can slow fast neutrons much more effectively than can any other element present in the soils. The density of the resultant cloud of slow neutrons is a function of the soil moisture content. Slow neutrons returning to the detector per unit time are counted. The moisture content is determined from previously determined calibration curves relating volumetric water content with counts or count ratios. Beryllium has the highest neutron yield of all elements, and thus has been almost exclusively used as the target material in radioactive neutron sources.

Advantages of neutron probes are the following (Chanasyk and Naeth, 1996):

- soil moisture can be measured regardless of its physical state,

- average moisture contents can be determined with depth,

- probes can be interfaced for automatic downloading of stored data,

- temporal soil moisture changes through seasons can be easily monitored,

- rapid changes in soil moisture can be detected,

- readings are related directly to soil moisture,

- measurements can be made repeatedly and non-destructively at the same time, and

- the large volume of soil sensed by neutron probes provides more reliable measurements of soil moisture that can be obtained from generally smaller gravimetric samples.

Disadvantages of neutron probes are that:

- inadequate depth resolution makes measurements of absolute moisture content difficult especially in layered soils,

- the moisture measurement may depend on physical and chemical properties of the soil, which are in themselves difficult to measure,

- care must be taken to minimise health risks, since the probes contain a radioactive source,

- accurate measurements of soil water at or near the soil surface cannot be made because of the neutron probe's sphere of influence,

- Although data can be downloaded automatically, the monitoring with depth normally requires field personnel to make individual readings, hence frequency of measurement is dependent on availability of personnel and budget constraints, and

- measurements of soil moisture by the neutron scattering method may be inaccurate when made in the presence of abrupt moisture changes, due to the large sphere of influence of the probes.

When the sphere of influence extends above the soil, neutrons that pass out of the soil into the air are not deflected back in significant amounts by the air. This loss results in a lower meter reading than is characteristic for the particular moisture content near the surface (Chanasyk and Naeth, 1996).

2.4.3 High frequency electrical techniques

The following three techniques makes use of the high dielectric constant of water to estimate the water content of soil:

▸ capacitance,

▸ portable dielectric probes (PDP), and

▸ time domain reflectometry (TDR), (Topp, *et al.,*1996).

At radio frequencies, the dielectric constant of water is about 80 and that of the other soil components, excluding air with a constant of 1, is of the range of 2 to 7. Hence a measure of the dielectric constant of soil in the radio frequency range is a good measure of its water content. (Topp, *et al.,*1996).

2.4.3.1 Capacitance

Thomas (1996) demonstrated the potential for using capacitance measurements at radio frequencies for determining the soil dielectric constant and thus its water content. Since then capacitance probes and circuitry have been diversified and rapid developments are being made.

The soil being measured acts as a dielectric in the capacitance probe and the instrument operates by automatically adjusting the frequency to tune a circuitry to resonance (Topp *et al.,*1996). The resonant frequency is related to the dielectric constant of the water in the soil. The circuitry has to be close to the probe and the modularization has allowed development of relatively inexpensive units.

Advantages of using the capacitance method of measuring water content.

A study carried out by Starr and Paltineanu (1998), to study changes in soil water content, at four soil depths (100, 200, 300 and 500 mm) as part of a research project to quantify temporal and spatial variation in soil properties under plough-tillage (PT) and no tillage (NT) maize, concluded that the multisensor capacitance provided the following advantages, amongst others, regarding the capability for field determination of:

▸ the 'apparent water holding capacity',

▸ the transition points between periods of high and low rates of the water loss,

▸ the small spatial scale effects of cultural practices on water infiltration,

▸ real time viewing of soil water dynamics over large areas, and

▸ irrigation scheduling strategies.

Disadvantages of the capacitance method of measuring water content

▸   Although this approach appears to offer much promise, there has not been sufficient testing and evaluation of the available devices,

▸   from in-field calibrations of capacitance and neutron scattering devices, Evett and Steiner (1995), cited in Topp *et al.,* 1996 concluded that the capacitance probe has poor precision and is unacceptable for routine soil water measurement, but could not identify specific causes of the poor performance.

2.4.3.2   Portable dielectric probes (PDP)

Portable dielectric probes operating at specific frequencies in the microwave range, measure electromagnetic wave propagation parameters from which the water content can be calculated (Topp *et al.,* 1996). In the portable dielectric probes a specific frequency signal is transmitted to the end of the probe placed on the soil surface. The properties of the signal reflected back depend upon the nature and the condition of the soil. From the measurement of the magnitude of the reflected signal in relation to that which was transmitted, the instrument calculates the dielectric constant and water content of the soil (Topp *et al.,* 1996).

Advantages of the portable dielectric probe (PDP):

▸   as a portable unit, it is easily used between sites and

▸   the PDP has great precision for measurement of the water content of the top 50 mm of soil.

Disadvantages of the portable dielectric probe (PDP):

▸   the PDP instruments, with the two high frequency probes have a shallow depth of penetration which presents difficulty in achieving adequate electrical coupling with the soil unless the surface is smooth, and

▸   it is not amenable to continuous, unattended *in situ* monitoring since it is a strictly portable unit.

2.4.3.3   Time domain reflectometry (TDR)

In time domain reflectometry, the velocity of propagation of a high frequency electromagnetic signal is determined. Propagation velocity of a TDR signal is determined by :

$$V = c.(K_a)^{-\frac{1}{2}} \quad \text{(Topp } \textit{et al., } 1996),\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 1$$

where :

V is the propagation velocity,

$c = 3 \times 10^8$ m.s^{-1} , is the propagation velocity of electrical signal in a vacuum or free space,

K_a is the apparent dielectric constant of the soil being measured.

The following explanation of how the TDR functions is based on work by Topp *et al.,* 1996. In the application of TDR to soil water measurements, a fast rise time voltage pulse travels in the soil guided by a transmission line or wave guide of length L, and the pulse reflects back from the end. The determination of the travel time, t, of the pulse travelling in the transmission line, yields the velocity, V during the two way travel as $V = 2L/t$. Equating the two expressions for V, gives the apparent dielectric constant of the soil measured as $K_a = (ct/2L)^2$ (Topp *et al.,* 1996). White et al (1994), Hook and Livingston (1996) and Ferre et al (1996) cited in Topp *et al.* (1996), have documented that K_a (dielectric constant) depends on θ (water content) according to a linear relationship of the form $K_a = C_1\theta + C_2$, where C_1 and C_2 are constants which depend on the soil. Such a relationship means that only two points of calibration are required.

Advantages of the time domain reflectometry technique:

- TDR techniques are useful for real time monitoring of the soil water balance, measurement of agricultural or forest water use efficiency or monitoring real time changes in water content for irrigation scheduling, and

- offer the possibility of sampling water contents at hourly intervals or even more frequently.

Disadvantages of the time domain reflectometry technique:

- TDR systems are typically limited to small plots of land due to the requirements of short cable lengths (< 25 m) (Starr and Paltineanu, 1998) and have been on the whole extremely expensive,

- Limitations of cable length requirements between instrument and probe currently restricts the choice of instruments and the larger separations require better quality cables and

associated cost increases, and

▸ Starr *et al.* (1996) mention on other limitation of the TDR technique as the difficulty of monitoring discrete soil depths without having to install rods from a soil pit.

2.4.4 Tensiometry

Field tensiometry is used to estimate the energy status of soil water. Due to the recent availability of accurate pressure transducers and data loggers, matric potential data can be obtained with high temporal resolution (Buchter, Hinz, Wydler and Fluhler, 1999). Although the construction of tensiometers can vary, all tensiometers consists of three basic components:

▸ a porous cup or plate,

▸ a pressure sensor and

▸ a chamber filled with water that connects the porous cup to the pressure sensor.

According to Cassel and Klute (1986), tensiometers measure the energy status of the soil water as follows:

As the water content of the soil surrounding the water filled porous tensiometer cup decreases, the energy level of the soil water decreases relative to that of the water in the tensiometer cup and in contact with the soil, and thus result in the reduction of water pressure in the tensiometer cup. If the soil surrounding the porous cup receives additional water, the soil water pressure is increased, and soil water flows through the walls of the porous cup into the tensiometer, thereby increasing the pressure of the water in the tensiometer cup. The energy status of the soil water is obtained from that of the tensiometer water, assuming that the latter is in equilibrium with the soil water.

Advantages of using tensiometry are the following:

▸ it is a relatively cheap method of monitoring the soil water status,

▸ can be used for continuous monitoring of the soil water status, and

▸ from the energy status of water one can tell flux and the direction of flow.

Disadvantages of using tensiometry are the following:

▸ they frequently exhibit significant diurnal fluctuations in measurements primarily as a result of temperature changes of the material in the tensiometer or the transducer tensiometer system (Cassel and Klute, 1986),

▸ require field personnel to replenish the tensiometer system with de-aired water at regular

intervals, and

▸ at soil matric pressures exceeding 1 m tensiometers fail.

The use of tensiometers for measuring soil water tension is the most popular technique in soil physics and irrigation research (Wang, Yates and Ernst, 1998). Buchter *et al.* (1999), recommend that tensiometer readings be taken after midnight or that tensiometer be insulated against air temperature fluctuations and radiation. A detailed discussion of the theory and application of tensiometers for field determination of soil water tension can be found in Cassel and Klute (1986).

Knowledge of the water status of soils and their relationship to plant development processes is necessary for the management of agricultural practices such as irrigation, drainage, and soil conservation. Distribution of water in the soil profile is the result of complex interactions between many variables related to climate, soil, crop and agricultural practices (Mahdian and Gallichard, 1996). The effects of these crops on soil water content and crop yield can be simulated with crop growth models that can be used as aids in interpreting experimental results as research tools, and as part of a decision support system for growers. To test the efficiency of existing strategies at Willowfontein and Taylors Halt, and /or to develop alternative irrigation strategies, computer simulation models had to be used for this purpose. It is for this reason that different computer simulation models are reviewed in the subsequent section. The idea was to identify the model appropriate for simulating localised physical processes under the conditions prevailing at both sites of study.

2.5 Soil Water Models

For the purposes of this review soil water models are classified into two categories i.e. numerical models using a cascading water balance approach and numerical models that solve the Richards' partial differential equation for unsaturated flow in soils. Water balance models follow the daily water budgeting approach. Examples of such models discussed in this section are the ACRU model (Schulze,1995), SWB model (Annandale, Benadé, Jovanovic, Steyn and du Sautoy, 1999) and CROPWAT model (Clark, Smith and El-Askari, 1998). Numerical models that solve the Richards partial differential equation for unsaturated flow in soils include, the SWACROP model (Mahdian and Gallichand, 1996), SWIM model (Ross, 1990) and the SWMS_2D model

(Simunek, Vogel and Van Genuchten, 1994)

2.5.1 The ACRU model

The Agricultural Catchment Research Unit (ACRU) model, is a daily soil water balance model that can be operated as a distributed or lumped small catchments model (Schulze, 1995). As a physical conceptual model, it represents a system in which important processes and couplings are idealised but describes the physics to the degree that physical processes are expressed explicitly. In this model less sensitive values e.g. temperature, reference potential evaporation are input at a monthly level and are transformed internally by Fourier analysis in a total evaporation model. It has been designed as a multilevel model, with either multiple options or alternate pathways available in many of its routines, depending on the level of available input data or the detail of output required (Schulze, 1995).

Sequence and processes in determining the daily soil water budget.

Listed below are the sequences and processes for a typical day which includes rainfall:

1. Evaporation of previously intercepted water,
2. Apportionment of maximum evaporation to maximum soil water evaporation and maximum transpiration,
3. Suppression of maximum transpiration under conditions of elevated atmospheric CO_2 levels,
4. Apportionment of available maximum transpiration to different soil horizons,
5. Estimation of actual soil water evaporation,
6. Estimation of actual transpiration from the plant,
7. Compensation for differentially wetted soil horizons,
8. Interception losses on a day with precipitation,
9. Precipitation abstractions in cracking soils,
10. Generation of quickflow from impervious areas,
11. Stormflow generation from a rainfall event, based on SCS runoff,
12. Saturated drainage processes, based on water volumes in soil horizons,
13. Accumulation of soil water under water logged conditions,
14. Redistribution of unsaturated soil water, based on relative volumes of water in different horizons,
15. Baseflow generation based on outflow parameter and volume of groundwater and

16.   Setting final values of the water budget.

ACRU is a multi purpose model that can be applied in design hydrology, crop yield modelling, reservoir yield simulation, irrigation water demand and supply, regional water resources assessment, planning optimum water resources utilisation and resolving conflicting demand on water resources (Schulze, 1995). The same principles of stormflow generation apply to irrigated areas as to general catchment areas.

In the ACRU irrigation routines the major losses that occur at the field, viz through surface runoff and deep percolation, are simulated on a daily basis as part of the irrigation water budget. Realistic values for other losses due to water conveyancing, storage and application do, however, need to be input in preparing a simulation. Tailwater losses from flood irrigation are not accounted for in ACRU and thus they must be accounted for by adding them to the field application losses. Typical values would range between 0.35 and 0.40 percent of total irrigation for the month (Schulze, 1995). Because of tilled soils and the high random roughness associated with irrigated fields, however, a coefficient of initial abstraction of 0.3 mm is recommended for irrigated lands (Schulze, 1995). The critical depth of the soil from which stormflow can be generated is set at 0.3 mm for irrigation routines (Schulze, 1995). More details on the theory and application of the ACRU model can be found in Schulze, 1995.

Advantages for use in small scale irrigation:
►   as a catchment based model with the lumped catchment option, ACRU can be used to simulate the daily water balance at a field scale,
►   data requirements can be met under small scale irrigation conditions,
►   since the ACRU model simulates daily water losses from the root zone due to deep percolation and / or surface runoff, it provides a useful parameter for evaluating the water use efficiency of different scheduling and / or management practices.

Disadvantages for use in small scale irrigation:
►   as a catchment based model which uses the water balance approach, ACRU cannot simulate localized zones of wetting and drying at variable time steps,
►   ACRU is not designed to simulate localised irrigation (hand irrigation) commonly used

in small scale agricultural conditions,

▶ ACRU accounts for runoff when irrigation amount (precipitation) exceeds the value representing initial infiltration and surface storage, which may not be correct with localised irrigation.

▾

2.5.2 The SWB model

Soil Water Balance (SWB) is a mechanistic, multi layer, daily time step soil water balance - generic crop growth model, developed from NEWSWB, a modified version of the model published by Campbell and Diaz (1988). According to Annandale *et al.* (1999), the soil water balance is computed by the SWB model as follows. A cascading soil water balance is used once canopy interception and surface runoff have been accounted for. Each soil layer is assumed to fill to field capacity and then pass on remaining water to the layer below. Any water that passes beyond the bottom layer is assumed lost to deep percolation. Potential evapotranspiration (PET) is calculated as a function of daily average air temperature, vapour pressure deficit, radiation and wind speed, adopting the international standardized FAO Penman-Montheith methodology (Smith *et al.,* 1996 cited in Annandale *et al.,* 1999). Two components of PET i.e. potential evaporation and potential transpiration are estimated from canopy cover. Actual transpiration is determined on a daily basis as the lesser of the root water uptake or maximum loss rate. Total soil water potential is used to determine the amount of water available for crop transpiration from each soil layer. The osmotic effect on crop growth is simulated by adding osmotic potential to the matric and gravitational soil water potentials. The osmotic potential is calculated as a function of ionic concentration. The daily dry matter increment (DM_i) is taken as the minimum of the water supply limited (Tanner and Sinclair,1983 cited in Annandale *et al.,* 1999) and radiation limited DM_i (Montheith 1977 cited in Annandale *et al.,* 1999). A stress index, (the ratio between actual and potential transpiration) is used as a limiting factor for canopy development.

In this model the required input data includes, planting date, latitude, altitude, rainfall and irrigation amounts and quality, and maximum and minimum daily temperature. In the absence of measured data, the SWB model estimates solar radiation, vapour pressure and wind speed according to the FAO recommendations. In addition, volumetric field capacity and permanent wilting point, initial volumetric soil water content, and the content of ionic species (Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, and SO_4^{2-}) are required for each soil layer. Since SWB is a generic crop growth model, the following crop specific parameters have to be experimentally determined in order to

accurately simulate the soil water balance: daily radiant transmission coefficient, vapour pressure deficit corrected dry matter water ratio, radiation conversion efficiency, day degrees required for crop development stages, cardinal temperatures, dry matter partitioning parameters, specific leaf area and stress index.

The SWB model simulates one dimensional water movement in the soil for both sprinkler/ flood and localized irrigation (Annandale *et al.,*1999). When irrigations are performed with drip or micro-irrigators, SWB calculates the soil water balance for both irrigated and non-irrigated surface layers. The irrigated fraction of the surface (f, portion of wetted area) is chosen in the input field table. According to Annandale *et al.* (1999), in the case of the drip or micro irrigated fields, the top soil layer water distribution is calculated for both irrigated and non-irrigated portions of the ground for rainfall, and only for the irrigated portion for irrigations. For further details on how the model handles chemical precipitation/dissolution an interested reader is referred to Annandale *et al.,*1999.

Advantages for use in small scale irrigation:
▸ the model is useful for simulating soil water balance at field scale,
▸ small scale irrigators may find the model useful for irrigation scheduling, since the model can simulate localized (drip or micro irrigators) irrigations,
▸ the model package contains the database (crop growth parameters) for most crops commonly grown in South Africa, and
▸ it is suitable for predicting crop water requirements when deficit irrigation strategies are applied.

Disadvantages for use in small scale irrigation:
▸ the model cannot simulate localised zones of wetting and drying at variable time steps,
▸ as a South African model, it has not been extensively verified under small scale irrigation conditions,
▸ suitability as an irrigation scheduling tool that could be used by small scale farmers or subsistence farmers is heavily reliant on support and advice by irrigation officers, not readily available and
▸ data requirements may limit the precision of the model when used under small scale irrigation conditions.

2.5.3 The CROPWAT model

CROPWAT is a practical tool to help agro-meteorologists, agronomists and irrigation engineers to carry out standard calculations for evapotranspiration and crop water use studies, and more specifically the design and management of irrigation schemes. It allows the development of recommendations for improved irrigation practices, the planning of irrigation schedules under varying water supply conditions, and the assessment of production under rainfed conditions or deficit irrigation.

Calculations of crop water requirements and irrigation requirements are carried out with inputs of climatic and crop data (Clarke *et al.,*1998). The development of irrigation schedules and evaluation of rainfed and irrigation practices are based on a daily soil water balance using various options for water supply and irrigation management conditions. Scheme water supply is calculated according to the cropping pattern provided. CROPWAT accepts monthly rainfall data only. For crop water requirements and irrigation scheduling purposes, the monthly total rainfall has to be distributed into equivalent daily values. In this model four methods are used calculating the effective rainfall from monthly rainfall data, and they can be found in Clarke et al.,1998

In CROPWAT, a revised Penman-Montheith method for estimating reference crop evapotranspiration is included, and to carry out the crop water requirements and irrigation scheduling calculations, the model requires monthly average reference evapotranspiration. This data is then smoothed into daily values (Clarke et al., 1998). The irrigation scheduling criteria of CROPWAT includes the definition of three variables:

- ▸ Application timing, i.e. when irrigation applications should be given. The default option is to irrigate when 100% of readily available moisture (RAM) is depleted,
- ▸ Application depths, i.e. defines how much water should be given in each irrigation application,
- ▸ Start of scheduling, defines the date at which scheduling calculations should start (Clarke et al., 1998).

CROPWAT uses one soil type only for all the crops in a cropping pattern. Percentage of initial soil moisture depletion determines the initial soil moisture deficit irrigation scheduling calculations for all the crops in a cropping pattern.

Advantages for use in small scale irrigation:

▸ it is a useful tool for a rapid assessment of the crop water requirements at a field scale and for the design and management of irrigation schemes and

▸ it is a generic model with a wide selection of default country and altitude specific

• climatic and crop data that render it suitable for use in data poor conditions.

Disadvantages for use in small scale irrigation:

▸ it is daily time step model, applicable at field scale, therefore it is not an ideal tool for assessing localized wetting and drying zones at variable time steps and

▸ CROPWAT uses only one soil type in a cropping, therefore soil water balance simulations may not be accurate, and

▸ it accepts only monthly data which will lead to inaccuracies.

2.5.4 The SWACROP model

Soil Water Actual Transpiration and Crop Production (SWACROP) model, is a transient, one dimensional model which solves the Richards' equation for vertical water flow in a heterogenous soil root system (Mahdian and Gallichand, 1996).

$$\frac{\partial h_w}{\partial t} = \frac{1}{c_o(h)} \frac{\partial}{\partial z} [k(h)[\frac{\partial h_w}{\partial z} + 1]] - \frac{s(h)}{c_o(h)} \dots\dots\dots\dots 2$$

Where:

h_w = soil water pressure head (m)

t = time (d)

c_o = specific water capacity (m³.m⁻³.m⁻¹) i.e. $c(h) = \dfrac{\partial \theta}{\partial h_w}$

θ = volumetric soil water content (m³.m⁻³)

z = vertical coordinate (m)

K = hydraulic conductivity (mm.d⁻¹), and

s = water uptake by roots (m.m⁻¹.d⁻¹)

This model solves the Richards' equation by finite difference and allows discretization of the soil

profile into a maximum of 40 compartments (i.e. 41 nodal points) within five different soil layers. The sink term s simulates water uptake by roots and depends on the soil water pressure head, h, and maximum extraction rate s_{max}.

$s(h) = \alpha(h)s_{max}$

where:

$\alpha(h)$ = reduction factor, and

s_{max} = maximum root water uptake rate (m.m^{-1}.d^{-1})

The maximum root water uptake rate is assumed to be uniformly distributed over the effective rooting depth:

$$s_{max} = \frac{T_p}{z}$$

where:

T_p = potential transpiration rate (m.d^{-1}), and

z = effective rooting depth (m)

The integration time step is determined automatically based on the values of the sink term and on variations of fluxes between compartments. Knowing the initial conditions (i.e. water content or pressure head distribution profile), and top and bottom boundary conditions, the system of equations for all the compartments is solved for each (variable) time step by applying the Thomas triagonal algorithm. For the top boundary, daily values of rainfall, potential soil evaporation (E_p), and potential transpiration (T_p) are required (Wesseling, Kabat, Brooks and Fedes, 1992). The value of potential transpiration (T_p), is calculated from the difference between potential evapotranspiration (ET_p) and potential evaporation (E_p) (Mahdian and Gallichand, 1996). According to Mahdian and Gallichand (1996), potential evapotranspiration can be read by SWACROP or calculated by different methods (Montheith, 1965, Rijtema, 1965, Pristley and Taylor, 1972, Penman, 1948). They also add that, potential evaporation is calculated based on the equation of Belmas *et al.*, 1983 or that of Ritchie, 1972. When the soil system remains unsaturated, one of three boundary conditions can be used i.e. pressure head, zero flux or free drainage. When the lower part of the system remains saturated, one can either set the groundwater level or the flux through the bottom of the system as an input (Wesseling at al, 1992). The rate of vegetation growth, both potential and actual can be simulated in the crop growth submodel which is linked to the main water model in a dynamic way. This submodel supplies information about the vegetation characteristics to the main water model throughout the

simulation period. However, both models can be run separately (Wesseling et al., 1992).

Output from the model includes daily values of infiltration, runoff, interception, potential and actual transpiration, potential and actual soil evaporation, flux through the bottom of the soil profile and root water uptake. SWACROP also provides for each compartment, daily values of soil water content, pressure head, hydraulic conductivity and water flux.

Advantages for use in small scale irrigation:

▸ SWACROP can be used to simulate irrigation at variable time steps, thus showing the maximum depth of the wetting front following an irrigation event,

▸ since the model is not data intensive, data requirements can be satisfied in small scale irrigation conditions and

▸ SWACROP can be used to predict water requirements and time of irrigation.

Disadvantages for use in small scale irrigation:

▸ SWACROP does not provide the user with an option to specify localised prescribed head and variable boundary condition,

▸ it is a one dimensional vertical flow model that can take up to a maximum of 41 nodal points, this simplifies the soil physics and can affect the precision of the model and

▸ SWACROP cannot be used to simulate pressure head and / or water content at a field scale.

2.5.6 The SWIM model

Soil Water Infiltration and Movement (SWIM) model is used for simulating water infiltration and movement in soils. Water is added as precipitation and removed as runoff, drainage, evaporation from soil surface and transpiration by vegetation. SWIM provides a greater number and variety of features than similar models including the following:

▸ Numerical solution of Richards' equation,

▸ Fast and accurate numerical scheme,

▸ Conservation of mass, even in fast, approximate solutions,

▸ Ability to handle nonuniform and layered soils,

▸ Ability to handle unsaturated, saturated and ponded conditions,

▸ Caters for transient soil surface conductance and storage,

- ▸ Calculates runoff and drainage,
- ▸ Allows simultaneous transpiration by several vegetation types,
- ▸ Extensive menus and help screens, and
- ▸ Ability to accept data in users preferred units.
- ▪

The SWIM model is not a daily time step model, the "water increment" parameter controls how large a step in time the simulator can accept. In this model simulation integration time steps are chosen so that the greatest water flow in the system, excluding transpiration, will be moved in one time step. A value of 5 mm is usually acceptable (Ross, 1990). The "conductance" parameter in the SWIM model determines how water flow through the soil surface is affected by a thin seal that may develop with time as raindrops impact it. Flow rate through the surface is given by the product of the surface conductance and the potential drop across the layer, whose thickness is assumed negligible (Ross, 1990). The conductance decreases exponentially with cumulative rainfall energy.

The SWIM model solves the Richards' equation for one dimensional flow of liquid water in soil using the "fixed grid" method. Transpiration rates are calculated from steady-state radial flow to roots during each print interval (or each day if the print interval is longer). These rates are then used as a constant sink term in Richards' equation (Ross, 1990). Ross (1990) also adds that the evaporation from the soil surface is calculated as a fraction of the potential using the humidity in equilibrium with the surface matric potential. These introduce many simplifications while accurate models would require more data that is seldom available (Ross, 1990). Further details on the SWIM model could be found in Ross, 1990.

Advantages for use in small scale irrigation:
- ▸ Useful for rapid assessment of the wetting front down the soil profile following an irrigation event,
- ▸ it can simulate localised zones of wetting and drying at variable time steps, and
- ▸ it is not data intensive, therefore, it is suitable for use in often data-poor small scale agricultural conditions.

Disadvantages for use in small scale irrigation:
- ▸ accuracy of the model can be suspect since it simplifies soil physics by using a one

dimensional fixed grid approach when solving the Richards' equation,

▸ it is not applicable at field scale and

▸ does not provide the prescribed head and variable pressure boundary condition, suitable for simulating localised irrigation methods commonly used in small scale agricultural

• conditions.

2.5.7   The HYDRUS-2D model

The HYDRUS-2D model is an updated version of the SWMS-2D and CHAIN-2D models. According to Simunek, Vogel and van Genuchten (1994), this model, which solves the Richards' equation for saturated /unsaturated water flow and the convection - dispersion equation for solute transport, may be used to analyse water and solute movement in unsaturated, partially saturated, or fully saturated porous media. It can also handle flow domains delineated by irregular boundaries since the Richards' equation is solved as a finite element numerical scheme.

An interesting feature of this model is that it allows prescribed head and flow boundaries, as well as boundaries controlled by atmospheric conditions. Depending upon the size of the problem, the matrix equations resulting from discretization of the governing equations are solved using either Gaussian elimination for banded matrices, or the conjugate gradient method for symmetric matrices and the ORTHOMIN method for asymmetric matrices (Mendoza *et al.,* 1991, cited in Simunek *et al.,* 1994).

The governing flow equation given by the modified form of Richards' equation in 2D, is based on the consideration of a two dimensional isothermal Darcian flow of water in a variably saturated rigid porous medium, and on the assumption that the air phase plays an insignificant role in the liquid flow process. The sink term represents the volume of water removed per unit time from a unit volume of soil due to plant water uptake.

The unsaturated soil hydraulic properties are described by a set of closed form equations, and a detailed description of these equations and scaling of soil hydraulic functions can be found in Simunek *et al.,* 1994. The scaling procedure is designed to simplify the description of spatial variability of the unsaturated soil hydraulic properties in the flow domain.

The solution of the Richards' equation requires knowledge of the initial distribution of the pressure head within the flow domain, and the model implements three types of system-independent interactions along the boundaries of the flow region.

These conditions are:-

▸ Specified pressure head boundary conditions,

▸ Specified flux boundary conditions, and

▸ Specified gradient boundary conditions.

In addition to the system - independent boundary conditions given above, the model considers three different types of system-dependent boundary conditions. One of these involves soil-air interfaces which are exposed to atmospheric conditions. The potential fluid flux across the interfaces is controlled exclusively by external conditions. However, the actual flux depends also on prevailing (transient) soil moisture conditions. Soil surface boundary conditions may change from prescribed flux to prescribed head type conditions and vice-versa (Simunek *et al.,*1994).

A second type of system-dependant boundary condition considered in the model is a seepage face through which water leaves the saturated part of the flow domain. The assumption made is that the pressure head is always uniformly equal to zero along a seepage face. Additionally, the code assumes that water leaving the saturated zone across a seepage face is immediately removed by overland flow or some other removal process.

Finally, a third class of system-dependent boundary condition in the model concerns tile drains. Similarly to the seepage face criterion, the program assumes that as long as a drain is located in the saturated zone, the pressure head along the drain will be equal to zero, the drain then acts as a pressure head sink. However, the drain will behave as a nodal sink / source with zero recharge when located in the unsaturated zone. The model and equations governing the mentioned boundary conditions can be found in Simunek *et al.,* 1994.

Advantages for use in small scale irrigation:

▸ since it is a two dimensional water and solute movement model that solves the finite element scheme, it can simulate localised zones of wetting and drying close to physical reality,

▸ the HYDRUS-2D can simulate water movement at variable time steps,

▸ the model allows for prescribed head and flow boundaries as well as boundaries controlled by atmospheric conditions, therefore, it can simulate accurately localised zones of wetting and drying occurring in small scale irrigation conditions, and

▸ data requirements can be met in small scale irrigation conditions.

Disadvantages for use in small scale irrigation:

▸ the model is not suitable for simulating water movement processes at a field scale and

▸ the prescribed head and flow boundary condition cannot be invoked simultaneously with the atmospheric boundary condition to simulate supplementary irrigation (hand irrigation) following rainfall events.

2.6 Conclusions

There is general agreement amongst many researchers that whilst larger schemes have been unsuccessful across Africa, small scale irrigation is seen as a promising means to raise both agricultural activity and employment. Although there are differences of opinion as to what constitutes a small scale irrigator, there seems to be consensus that SSIS are predominantly low-tech gravity systems rather than pressurised systems.

Women involvement and contribution to small scale agricultural development can no longer be ignored. There is enough evidence to suggest that their number in small scale irrigation has increased, and as such their problems need to be addressed. There are other issues e.g. constraints and opportunities and management issues that would have to be carefully examined to achieve success with small scale irrigation development.

Lessons from the Sri Lankan rehabilitation programme are that the need to first understand and appreciate existing patterns of water allocation and distribution and the organisational basis that surrounds them is fundamental to the success of the rehabilitation programme. In addition to co-ordinated activity between implementing agencies, there should be effective mechanisms in place to monitor how government officials execute their duties, and that programme implementation should not be seen to be a "taking over and handing over" exercise. Finally, there is a need to

involve farmers more effectively in all phases of the rehabilitation process. This means more than merely upholding the rhetoric on farmer participation. Unless farmers are effectively involved in the rehabilitation process, there will be irrevocable consequences for system maintenance in the long run.

It is clear that both RRA and PRA methodologies have their own advantages and disadvantages. It can be concluded that the responsibility lies with the researcher to choose a methodology that he/she thinks will work effectively in his/her area of research. In Africa both these methodologies have been used successfully, but the emphasis seems to be on the use of the PRA methodology.

Since one of the objectives of the study was to test and determine whether instrumentation could be used to monitor and understand soil water dynamics under small scale agricultural conditions, for accurate and continuous monitoring of soil water, the time domain reflectometry (TDR) technique, as well as the neutron probe moisture meter appeared to be the promising options.

But for the purposes of this study, the neutron probe moisture meter would not be suitable, mainly because of the problem of the sphere of influence, which would lead to inaccurate moisture readings at soil depths near the surface. This is where most of the roots are found for the crops under study.

Given the cost implications of use the other monitoring techniques, and the fact that complete safety of instruments could not be guaranteed, tensiometry appeared to be a promising option for continuous soil water monitoring in the sites of study. Its advantages being the measurement of soil water tension, the monitoring of water flux dynamics, and the establishment of the direction of water flow.

The other objective was to evaluate current irrigation practices using an appropriate modelling tool. Therefore from the review of models, it appears that the soil water models that use the water balance approach at daily time steps are useful for long term water balance studies as well as for a rapid assessment of water balance at field scale.

For a study aimed at understanding irrigation efficiency, from a water application view point, such models would not be appropriate. A numeric model that simulates soil water dynamics

close to physical reality at variable time steps would be the one of choice. Since the HYDRUS-2D could accurately simulate localised zones of wetting and drying close to physical reality at variable time steps, and because of the other advantages it has for use in small scale irrigation, it was chosen for simulation modelling in this study.

3. METHODOLOGY

The study methodology is divided into three parts, namely a social system appraisal, a technical system analysis and soil water modelling. Based on this three part approach, appropriate recommendations for improvements (efficiency) in SSIS can be offered. Efficiency in the context of this study means the best management practices, including the application of water amounts which optimises crop yields.

3.1 Introduction

Data collected in the field are essential for meeting the objectives of this type of study. The data are then analysed to understand either the social or the physical processes taking place at the scale under investigation. Data are also useful as input parameters for modelling scenarios as well as for verification of the simulated versus the observed processes.

The objective of the field work carried out in this study was to collect data on a continuous basis in order to understand the soil water dynamics prevailing under the described conditions. Data were collected at both sites (Willowfontein and Taylors Halt). Since one of the primary objectives of the study was to establish crop water use efficiencies in small scale agricultural conditions, the following physical data were collected and the process of data collection was automated wherever possible:

- soil moisture data,
- rainfall data,
- irrigation data,
- hydraulic conductivities (saturated and unsaturated conductivities),
- water retention characteristics and ground water observation.

3.2 Description of the Research Sites

Figure 1 shows the geographic location of where the research work was carried out in the KwaZulu - Natal province in South Africa.
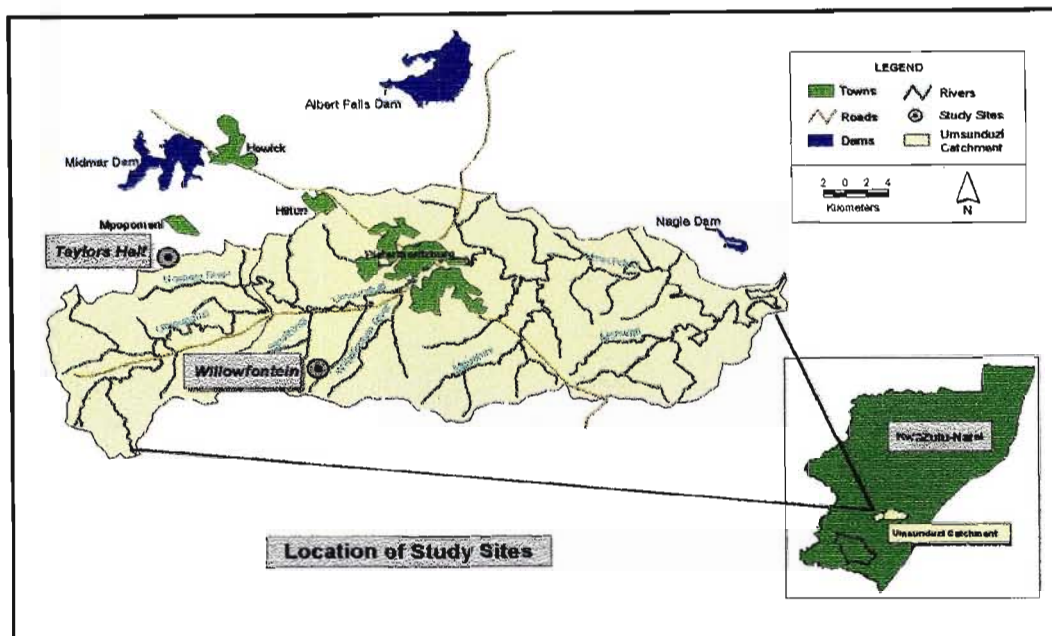
Figure 1   Map showing the location of study sites in KwaZulu-Natal.

3.2.1   Willowfontein

The Willowfontein research site is a community vegetable garden approximately 0.7 ha in extent. It is located in an underdeveloped area of KwaZulu-Natal at Willowfontein, about 23 km south of Pietermaritzburg City Centre, at latitude 29°42' S and longitude 30°20' E and at an altitude of 850 m. It is on a north facing hillslope with an average gradient of some 13%. The mean annual precipitation of the area is 800 mm. The vegetation at Willowfontein surrounding the research site comprises indigenous veld grasses in good condition. At a distance of about 200 m from the south east corner of the fence surrounding the site is a small farm dam (Figure 2). Growers maintain that the dam is a major source of irrigation water since it never runs dry being constructed across a perennial stream. Irrigation water flows from this dam along a channel into the cultivated plot. It is then diverted to irrigate different sub-plots by short furrow irrigation according to the irrigation requirements of the growers. Excess water is led off to a separate non-perennial stream on the west of the plot.

There are about 30 000 people residing in Willowfontein. It is estimated that some 60% of these people are unemployed and under such circumstances vegetable gardens are rated highly by the community, since they are an important source of food as well as means of augmenting family income.
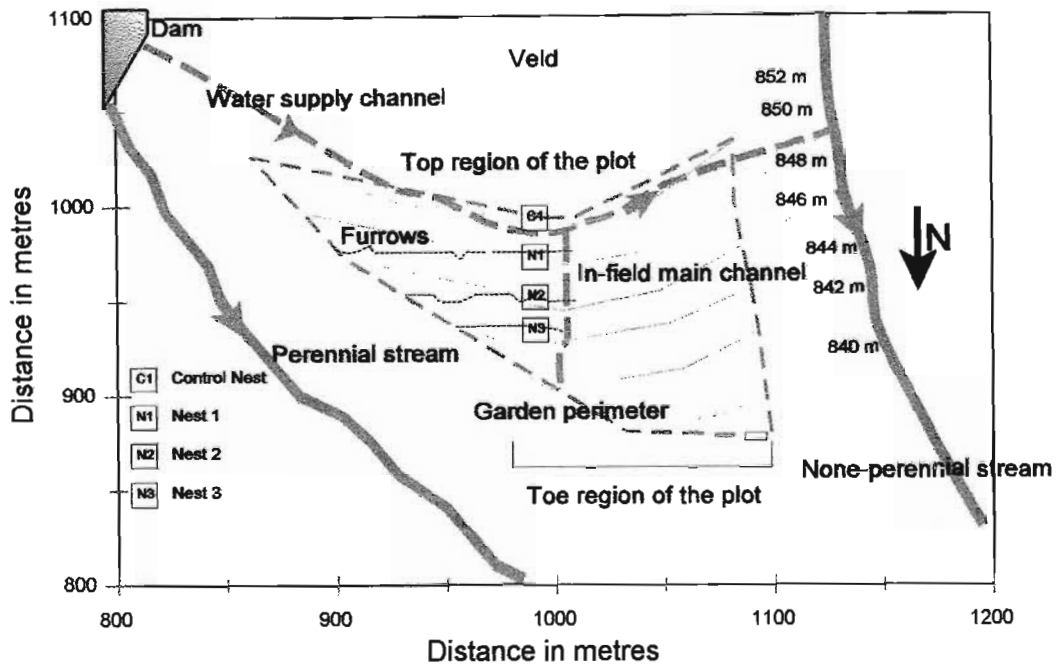
Figure 2   Diagrammatic layout of the Willowfontein site.

3.2.2   Taylors Halt

The Taylors Halt research site is a community vegetable garden approximately 0.5 ha in extent. The village in which it is located is called Kwadulela, (but in this study the site is referred to as Taylors Halt) and represent an element of a developing South Africa.   It is situated at latitude 29°36' S and longitude 30°11' E. It is on a north facing hillslope with an average gradient of 11%. The mean annual precipitation of the area is 875 mm and the altitude is 1273 m.   The vegetation at Taylors Halt (Kwadulela) surrounding the site can be described as veld in good condition.   At the toe part of the garden (Figure 3) is a non-perennial stream which is the source of irrigation water.   The fact that flow is seasonal poses serious irrigation problems in winter when it runs dry. It is for this reason that very little gardening activity takes place in the dry winter months.

Kwadulela village is about 45 km south west of Pietermaritzburg city centre and distinctly rural in nature. The residents/growers are heavily reliant on the produce from the community gardens for vegetables. The commitment they display and the amount of time and effort they put into their gardening activities is clear evidence of this fact. The irrigation system used at this site involves collection of water from the nearby stream using containers (buckets) and during irrigation, smaller containers are used to apply water to the crops.   The volume of water

to each crop per irrigation event is based entirely on the discretion of the irrigator and is thus reliant entirely on knowledge gained from past experience. However, it was subsequently established that on average the cultivators applied approximately 18 mm of water local to the crop during irrigation.
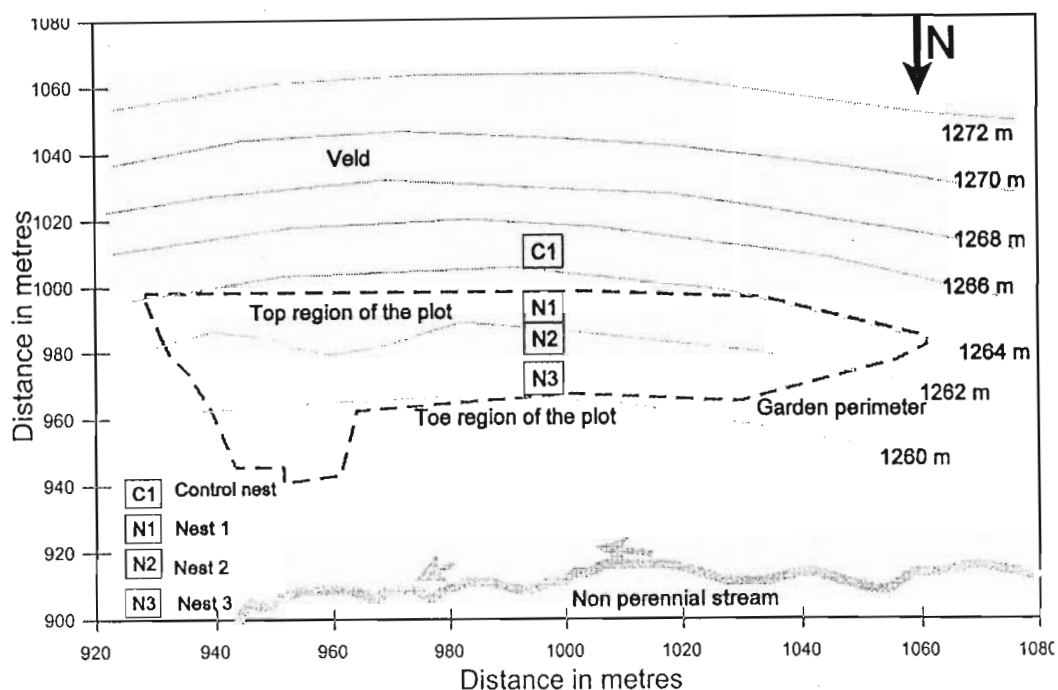
Figure 3   Diagrammatic layout of the Taylors Halt site.

3.3   Social System Appraisal

Data collection regarding the social system required that an appropriate methodology be adopted. The following is a discussion of the methodology that was used in this study.

3.3.1   Data collection on social processes

Since research of this nature had not been carried out in the described conditions before, consultation became necessary at the very outset so as to inform all the stakeholders about the intentions of the research, and to solicit their input into this type of work. Consultation included the Greater Edendale Environmental Network (GREEN) and the Institute for Natural Resources (INR). This was essential in order to tap on experience and knowledge of organisations and agencies that enjoyed credibility within these communities. Consultation also included communication with tribal authorities, the Department of Agriculture and the community

gardening groups. Meetings were arranged with the community gardening groups and in each meeting the details of the research to be carried out were explained, including foreseeable activities that would jeopardise the success of the project. Community members were then prompted to suggest mechanisms of ensuring that the project intentions were realised without any negative interference.

At both sites the method of collecting data on organisational and behavioural issues surrounding water use and allocation, involved observations and informal discussions with individual growers. This was done during the process of carrying out on site-experiments. Structured interviews with leaders from each of the groups were also held. Questions asked during these interviews are summarised in Appendix G.

3.4   Technical System Analysis

The climatic information typical of both sites is given in Table 1. These data were obtained from the climatic station, 0239756W situated at 29°36' S, 29°36'E. This station is about 20 km from both sites and was the only station closest to both sites with a record long enough to calculate evaporation and temperature statistics. The evaporation and temperature data show potential evaporation exceeding rainfall for every month of the year. This is cause for concern in crop water use studies as it would affect the soil water crop continuum, thus necessitating proper irrigation scheduling and water application efficiencies for optimum crop yields.

3.4.1   Monitoring

At field scale the instrumentation installed comprised one automated recording raingauge (standard tipping bucket raingauge), 12 automated tensiometers, 5 loggers and four piezometer tubes. Irrigated profiles and the control were instrumented at both the Willowfontein and Taylors Halt sites (Figure 4). Figure 5, shows the surface topology at nest 2 of the Willowfontein site and the expected water redistribution down the soil profile at both sites. All these instruments (except the raingauge) were made at the School of Bioresources Engineering and Environmental Hydrology (SBEEH). The sections which follow discuss the preparation and installation of these instruments and the monitoring approach used.

3.4.1.1 Hydrometeorological instrumentation.

One standard tipping bucket raingauge (Figure 4) was installed by the SBEEH in September 1998 at Willowfontein and in November 1998 at Taylors Halt. This automated recording raingauge was installed on a suitable spot on the edge of the cultivated field. Break-point rainfall was recorded with the data being written to a memory module. These data were downloaded monthly. The rainfall data comprised a good data set with no missing records for the period September 1998 to January 1999 for Willowfontein and November 1998 to May 1999 for Taylors Halt.

Table 1   Monthly climatic information typical of both sites

Month	Rainfall (mm)	A-Pan[1] Evaporation (mm)	Monthly means of daily temperatures		
			Maximum (°C)	Minimum (°C)	Average (°C)
January	150.4	180	28.1	17.4	22.8
February	121.3	160	27.6	17.3	22.5
March	115.4	150	27.5	16.0	21.8
April	53.9	120	26.3	12.0	19.2
May	23.8	100	23.9	6.8	15.4
June	10.0	90	22.2	2.6	12.4
July	11.7	100	22.9	2.2	12.6
August	32.3	130	23.5	5.3	14.4
September	60.1	150	24.9	10.0	17.5
October	97.9	160	25.1	12.6	18.9
November	120.1	160	25.8	14.4	20.1
December	135.1	180	27.4	16.2	21.8
Yearly Average	932.0	1680	**25.4**	**11.1**	**18.3**

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[1] A pan evaporation estimated from the data that were obtained from climatic station 0239756W.

3.4.1.2 Layout of the experiment and monitoring approach

Figure 4 below shows how instruments were arranged in the field on each of the sites. Figure 5 depicts topology around nest 2 at Willowfontein and expected water movement down the soil profile.
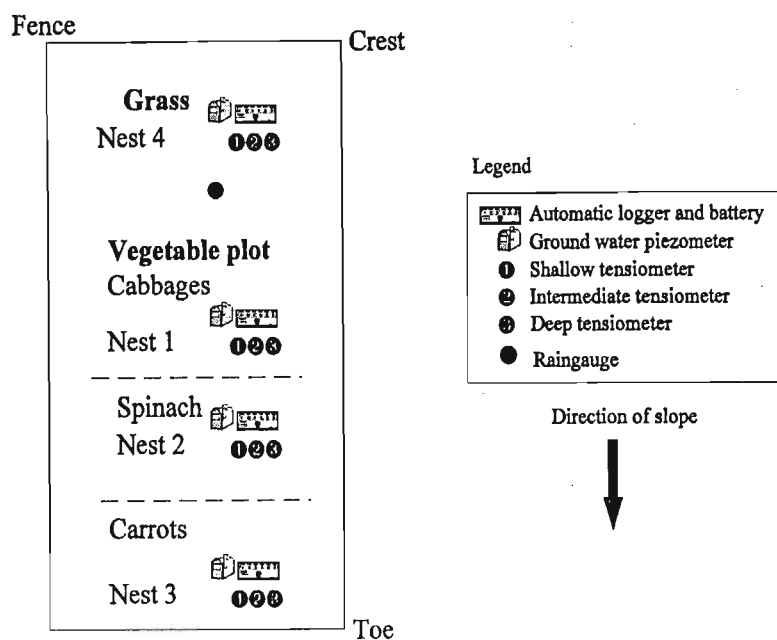
Figure 4   Experimental layout of the instrumentation, typical of both sites

3.4.1.3 Tensiometer nests

To measure the water content of the soil at both the sites, one option was to use the neutron moisture meter (NMM). Owing to constraints like the problem of the sphere of influence which would have caused inaccurate readings to be recorded at shallower depths, the cost implications of using this technique for continuous monitoring of soil water content at both the sites and other logistical problems, automated tensiometers were selected and installed to measure the capillary potential of the soils at four locations along an established transect. Tensiometers were installed at both sites (Figure 6) and were selected for use in this study with the confidence that they have a successful track record for continuous measurement of soil water tension in the field (Ley and Thomas,1994). At each site four tensiometer nests were installed. Nests 1 to 3 were within the cultivated field while Nest 4 the control, was outside the cultivated field in the veld (Figure 4). Pressure transducers were connected to each tensiometer and the signal was recorded to a four channel logger, powered by a 6V battery. Each logger and battery were housed in a PVC pipe as shown in Figure 7. The following sections discuss the components of each tensiometer nest.

Topology Willowfontein Nest 2
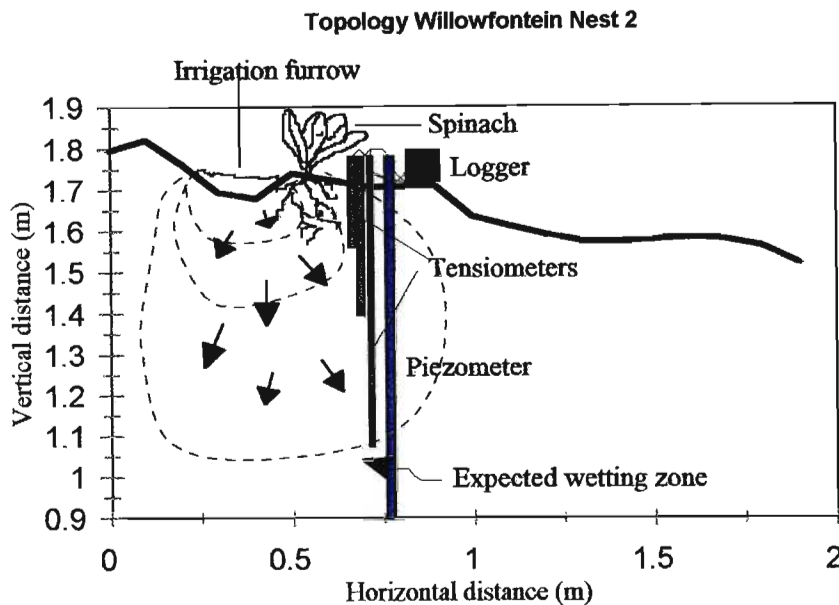
Figure 5   Surface topology and profile monitoring of Nest 2 at Willowfontein

3.4.1.4   Tensiometer installation

In total 12 tensiometers were installed at each site. These could be divided into three sets with respect to their lengths which ranged from 0.11m to 0.9m. Since these tensiometers were made by the SBEEH, they were made such that pressure transducers could be easily connected and such that they could be easily maintained *in situ*. Figure 8 shows an example of one such modified tensiometer. A PVC pipe was cut to the desired tensiometer length and a ceramic tip with a bubbling pressure of 1 bar was glued on to this PVC pipe. Perspex rods were cut, machined to fit the diameter of the PVC pipe, drilled in the middle to make a hole with a diameter just enough for the inner tubing to go through and then glued to the top of the tensiometer. A hydraulic hose connector was used to connect the tensiometer inner tubing to a section of transparent tubing which was in turn connected to the negative port of the differential pressure transducer. The positive port of the pressure transducer was left open to the atmosphere. The tensiometers were replenished with de-aired water once every two weeks.

Figure 6   Tensiometer installation at Taylors Halt (Left) and Willowfontein (Right)
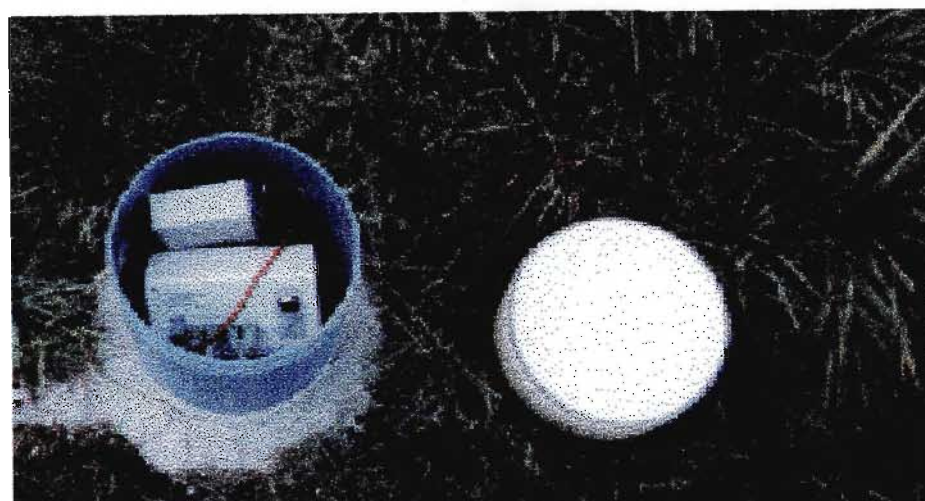
Figure 7   Logger and battery housed in a tubing, typical of both sites

3.4.1.5   Pressure transducers

The Motorola MPX5100 piezoresistive pressure transducer was connected to each tensiometer. These state of the art transducers can be described as a " one chip signal conditional temperature compensated monolithic silicon pressure sensors" (Esprey, 1997). This means that no significant error arises due to changes in temperature during operation (0 to 50°C). These sensors have a pressure range of 0-1 bar and are powered by a 5.25V supply. They have a positive port open to the atmosphere and a negative port connected to the tensiometer water. A silicon diaphragm found in these ports within the transducer casing, changes resistance characteristics in response to a change in pressure within the tensiometer.
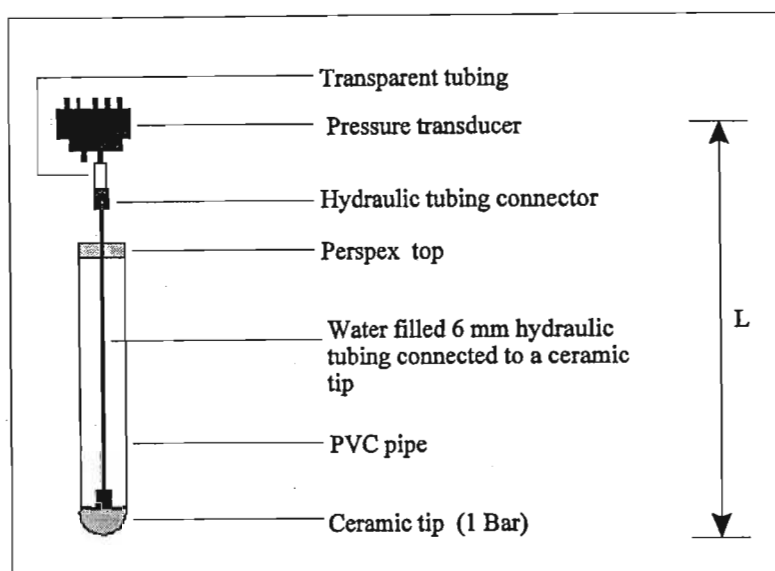
Figure 8   Modified tensiometer developed by the SBEEH.

At pre-programmed time intervals, an electronic signal is sent to a monitoring device and is recorded. These transducers have been calibrated so that this electronic signal (voltage) can be converted to a corresponding capillary potential, or suction head of the soil (Esprey,1997).

To calibrate the pressure transducers a 6 Volt power source, a logger, a vacuum pump and a mercury U tube manometer was used. The negative port of the pressure transducer was connected to the vacuum pump which was also connected to the mercury manometer. Four pressure transducers were connected to the logger and calibrated simultaneously. Suction was then applied using the regulator valve on the vacuum pump to change the head in the mercury U tube, corresponding readings were taken within the range of 0 to 700 mm Hg. On reaching the maximum suction head, corresponding voltage readings were taken, decreasing the pressure to check whether the transducer gave the same readings as when the pressure was increased to the same points. These data are illustrated in Table 2, which shows the voltages to be similar for identical points. Capillary potential pressure heads were calculated for all tensiometers using the transducer calibration equation and the length, L, of the tensiometer measured from the pressure transducer to the ceramic tip below the soil surface (Figure 8). Equation 3 is an example of the equations used to calculate the capillary pressure head. The example relates to transducer TH4 connected to a tensiometer at Nest 2, Taylors Halt.

Table 2 An example of voltages recorded by pressure transducer TH4 for corresponding suction heads of mercury with a regressed equation. (These data show the accuracy of the transducer under hysteresis conditions.)

Suction (Increasing)		Voltage	Suction (Decreasing)		Voltage
mm Hg	mm H$_2$O	(mV)	mm Hg	mm H$_2$O	(mV)
0	0	166.5	648	8812	3336.0
205	2788	1154.0	607	8255	3116.0
407	5535	2148.0	507	6895	2632.0
507	6895	2636.0	406	5521	2137.0
608	8268	3122.75	206	2801	1159.0
648	8812	3333.5	0	0	166.5
EQUATION: h (mm) = 2.7849 * V - 442.812 (r^2 = 0.99)					

$$h = (-442.812 + V * 2.7849 - L) / 1000 \dots\dots\dots 3$$

where **h** = Capillary pressure head (m)

V = Voltage (V)

2.7849 = Slope of transducer calibration equation.

-442.812 = Intercept of transducer calibration equation.

L = Length of tensiometer from pressure transducer to ceramic tip of the tensiometer (mm)

3.4.1.6   Robust loggers

Since the intention of the study was to establish water application efficiencies, it was important to monitor water redistribution down the soil profile on a continuous basis. Hence the data recording process had to be automated. To achieve this purpose, loggers developed by the SBEEH were used for automatic and continuous recording of data. These are inexpensive, robust loggers that have proven to be successful in recording tensiometer data. Pressure transducers are connected to these loggers which have an amplified and temperature compensated output in the

range of 0 to 5 Volts. A 6V battery powers both the logger and the transducer. Figure 9 illustrates one such logger.
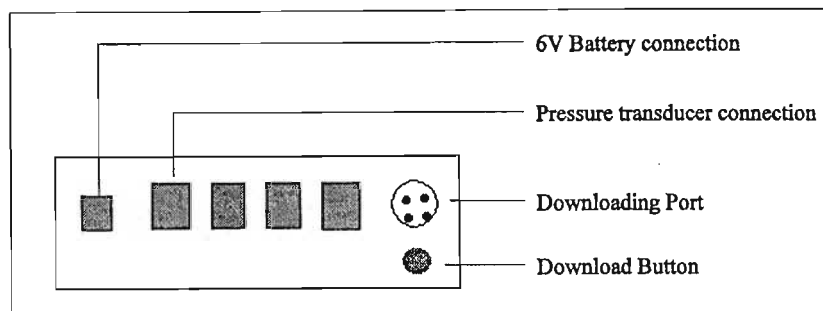
Figure 9   Logger developed by the SBEEH to record electronic signals from attached pressure transducers.

A maximum of four pressure transducers can be attached to each logger. Pressure changes inside the tensiometer are digitised and saved to non volatile memory at pre-determined time intervals. This time interval can be changed depending on how frequently data are required. Before readings are recorded, the logger performs a voltage check on the battery. If the voltage of the battery is below a predetermined threshold, a low battery symbol is recorded in the data file.

For this research the data storage time was set at 12 minute intervals, with the signal from each sensor being sampled 250 times, averaged and then stored. Functions built into the logger software automatically switch off the logger and power to the pressure transducer between readings. This power saving technique enables the battery to remain charged for up to 68 days when sampling at this 12 minute interval. Data can then be downloaded on site to a laptop PC (Figure 10) by depressing the button shown in Figure 9. Data are subsequently imported into a spreadsheet program and converted to capillary potentials using equations similar to equation 3.
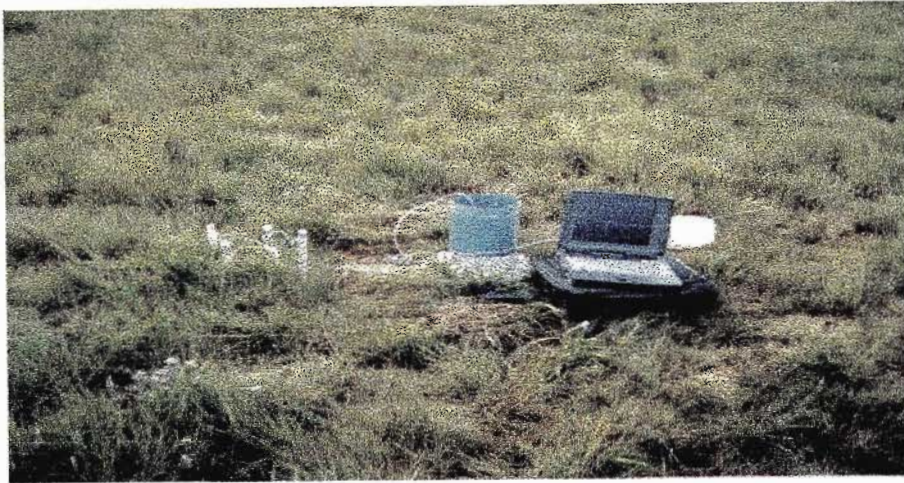
Figure 10   A laptop computer used for downloading data from a logger
connected to tensiometers.

3.4.1.7   Installation of a tensiometer nest

The location and arrangement of tensiometer nests can be seen in Figure 4. During installation
a tensiometer was inserted into a hole augured to the desired depth. A muddy slurry was used
to maintain contact between the ceramic tip and the surrounding soil. Tensiometers were filled
with de-aired water. A syringe was used to remove air bubbles from the negative port of the
pressure transducer. Air bubbles in the tensiometer give incorrect reading, so it is essential to
ensure that air bubbles are removed.

Tensiometers were replenished with deaired water once every two weeks. The battery had to be
replaced with a recharged unit every 60 days. A water bottle with long thin tubing and a syringe
was used to replenish the tensiometers. This was done after the data had been downloaded so as
not to affect recorded data.

3.4.1.8   Piezometer tubes

Figure 4 shows the position of the piezometer access tube next to each tensiometer nest. Using
a 0.10 m diameter bucket augur, holes were augured to the bedrock depth. Each of these depths
was recorded. PVC pipes with 0.05 m diameter were machine slotted. Each PVC pipe had about
1.5 m slotting from the base upwards. The slots were made so as to allow groundwater to
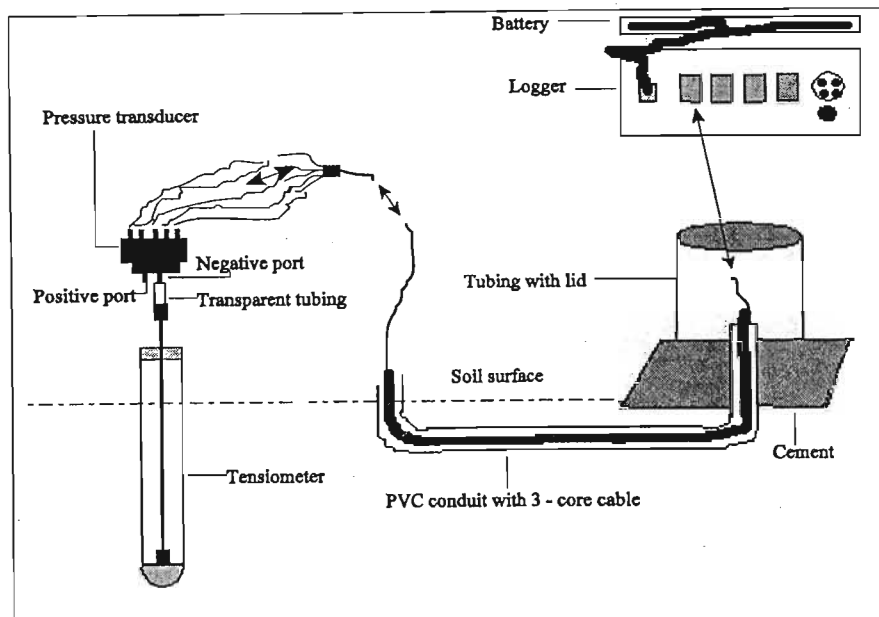
Figure 11   Tensiometer nest showing all components (Not drawn to scale).

enter the piezometer tube from the surrounding soil. Each tube had a sealed base to prevent soil and sediment moving into the tube. Upon insertion into the augured hole, coarse "Umgeni sand" was used to pack the area surrounding the tube and a clay plug was inserted at the surface to prevent water from moving down the sides of the tube. To determine the depth to the water table, a measuring tape was inserted into the piezometer access tube up to the base of the piezometer tube. The wetted section of the tape gave some indication to the depth of the water table below the surface. Figure 12 shows a typical observation well.

3.4.2   Measurement of hydraulic characteristics

Obtaining soil hydraulic properties representative of field soil conditions is important in understanding and simulating the dynamic processes of water and solute movement in the soil (Wang, Yates and Ernst, 1998). Because traditional transient laboratory methods such as outflow or evaporation experiments, show relatively little sensitivity to the hydraulic conductivity at near saturated to saturation levels, there is a trend towards determining the hydraulic conductivity in the wet range with steady state experiments, such as the tension disk infiltrometer method or the crust method (Simunek, Wendroth and van Genuchten, 1999). According to Simunek *et al.*, 1999, infiltration rates effectively integrate properties of the porous media underneath the disk infiltrometer, including the influence of local scale heterogeneity, different soil structure and
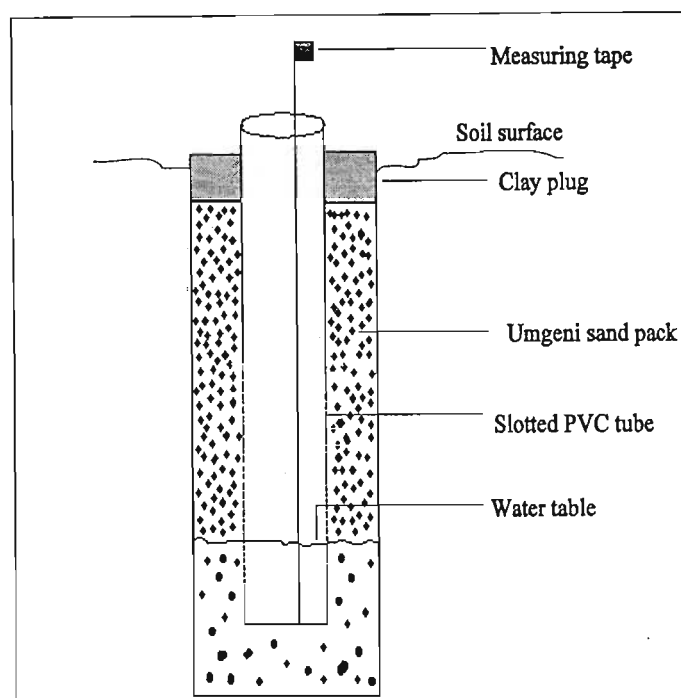
Figure 12   Unconfined aquifer, piezometer tube (Not drawn to scale)

texture irregularities, preferential pathways, layering and anisotropy. Hence they maintain that infiltration rates provide a good way for estimating the effective near saturation hydraulic properties. Some of the commonly used methods for estimating hydraulic parameters are the Wooding's steady state approximate solution, Darcy-Buckingham flux law and a transient state sorptivity method. A brief technical description of each of these methods can be found in Wang *et al*, 1998. In their study to evaluate the accuracy of these methods in estimating soil hydraulic properties, Wang *et al*. (1998) found the Wooding's steady state method to work reasonable well. They recommended that the other two methods be used as alternatives to Wooding's approach. This is because these two methods produced good results relative to the spatial variability of soil physical properties in the field. They added that the sorptivity method may become more useful in fine textured soils where steady state infiltration is difficult to reach.

3.4.2.1   Hydraulic conductivity measurement

Data on saturated hydraulic conductivity (K_s) and unsaturated hydraulic conductivity (K(h)) at both Willowfontein and Taylors Halt sites were collected using the double ring infiltrometer and the tension infiltrometer techniques, respectively. The method of Ankeny, Ahmed, Kaspar and Horton (1991) was used to calculate the unsaturated hydraulic conductivities K(h). This simple

and rapid field technique of determining field unsaturated hydraulic conductivity is based on Wooding's (1968) steady state water infiltration into soil from a circular source of radius r. The advantages of the Ankeny *et al.* (1991) method were that:

- It allowed steady state measurement of infiltration rates, and knowledge of the initial water potential or content was not required,

- Soil pore structure was not disturbed by driving a ring into soil to obtain one dimensional flow. Consequently, larger pores were not truncated or collapsed, and infiltration from the larger pores was less likely to be underestimated,

- Measurement at different tensions were taken on the same soil surface and

- Calculation of hydraulic conductivities was relatively simple.

An interested reader is referred to Ankeny *et al.* (1991) for the theory on this technique of determining *in situ* hydraulic conductivities.

At both the sites a representative spot in the middle of the field was identified and a pit was established at that spot. The tension infiltrometer and the double ring infiltrometer tests were carried out at the soil surface and down the profile at increments of approximately 0.30m and to a maximum depth of approximately 2m. Hydraulic conductivities for both the sites are shown in appendix TH1 and WF1 for Taylors Halt and Willowfontein respectively. Figure 13 shows a tension infiltrometer test in operation at Willowfontein.

3.4.2.2 Water retention characteristics

The relationship between water content and tension is a fundamental hydraulic characteristic for any soil and essential for simulating soil water dynamics. Many other hydraulic properties are derived from this basic relationship (Wang *et al.*,1998). *In-situ* measurements of water content and corresponding capillary pressure head using time domain reflectometry and tensiometers respectively, are useful for generating water retention characteristic curves. One other method for generating the water retention characteristic curve is the pressure plate outflow method, which was introduced by Gardner, 1956, in which an initially saturated soil is subjected to a series of step increases in air pressure with the drainage or outflow measured after each pressure step increase.

Soil samples collected from each soil profile at both the sites were used to characterise the water retention properties of the soil. The method used was the controlled outflow method developed

by Lorentz, Durnford and Corey, 1991. This method is used to determine each point on the retention curve by equilibration of the capillary pressure at a fixed saturation. Details of this method can be found in Lorentz, 1993. These water retention data, together with the curve fitting procedure, where van Genuchten (1980) functions were fitted to actual data, are presented in appendix D and E for Willowfontein and Taylors, Halt respectively.

Figure 13   Tension infiltrometer test in operation at Willowfontein

3.5   Modelling (The HYDRUS-2D model)

In order to simulate soil water dynamics close to physical reality at variable time steps, a two dimensional soil physics model, Hydrus 2D (Simunek, Sejna and van Genuchten, 1999) for simulating the movement of water, heat multiple solutes in variably saturated media was used. The Hydrus 2D model is an updated version of the SWMS-2D and CHAIN-2D models (Section 2.4.6).

3.5.1   The finite element grid, initial and boundary conditions

A finite element grid (Figure 14) was used to represent the soil profile at a local scale beneath and adjacent to the crop and tensiometer nest. The Willofontein and Taylors Halt soil profiles were represented by 0.9 m x 2 m , and 1.28 m x 2 m grids, respectively. No flow boundary surfaces were designated on the sides of the grid with the top of the grid designated as an atmospheric boundary surface, except in the irrigation zone (Willowfontein only). In this zone time dependent
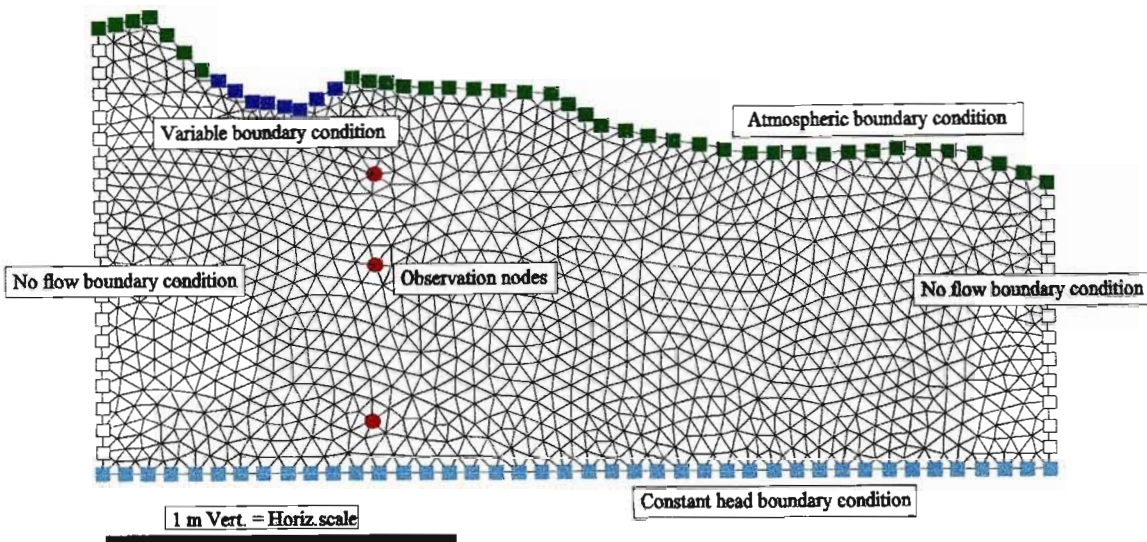
Figure 14   Typical Hydrus 2D finite element grid of soil profile at Nest 2 of the Willowfontein site.

pressure heads were imposed to represent furrow irrigation. On the base of the grid a constant pressure head of 1200 mm was specified as this reflected observed tensions at this depth. Initial soil moisture conditions were specified as those from field measured tensiometer data for the three soil horizons. The soil hydraulic conductivities were established from field measurements, with hydraulic parameters fitted to the van Genuchten (1980) curve.

Tables 3 and 4 show soil hydraulic parameters for the three horizons at Willowfontein and Taylors Halt respectively. Establishment of these parameters is explained in section 4.2.1.2

Table 3 Willowfontein soil water hydraulic parameters.

Depth (mm)	Q_r	Q_s	Q_a	Q_m	α	n	K_s	K_k	Q_k
Surface	0.31	0.497	0.31	0.497	0.0050	1.8	0.041	0.0398	0.497
300	0.29	0.443	0.29	0.443	0.0040	2	0.021	0.019	0.443
1240	0.158	0.443	0.158	0.443	0.0090	1.3	0.016	0.0159	0.443

Table 4 Taylors Halt soil water hydraulic parameters

Depth (mm)	Q_r	Q_s	Q_a	Q_m	α	n	K_s	K_k	Q_k
Surface	0.29	0.661	0.29	0.661	0.0035	1.5	0.0219	0.0199	0.661
890	0.3	0.721	0.3	0.721	0.0019	1.4	0.0211	0.0191	0.721
1060	0.2	0.609	0.2	0.609	0.0030	1.4	0.0132	0.0099	0.609

where:

Q_r, is the residual soil water content ($mm^3.mm^{-3}$),

Q_s is the saturated soil water content ($mm^3.mm^{-3}$),

Q_a is the parameter in the soil water retention function (mm^{-1}),

Q_m is the parameter in the soil water retention function (mm^{-1}),

α is the parameter in the soil water retention function (mm^{-1}),

n is a dimensionless parameter in the soil water retention function,

K_s is the saturated hydraulic conductivity ($mm.h^{-1}$),

K_k is the unsaturated hydraulic conductivity ($mm.h^{-1}$),

Q_k is the volumetric soil water content corresponding to K_k ($mm^3.mm^{-3}$),

3.5.2 Root water uptake parameters

The root water uptake parameters for both sites are given in Table 5.

Table 5 Root water uptake parameters for Willowfontein and Taylors Halt sites.

PO (mm)	PO_{pt} (mm)	P2H (mm)	P2L (mm)	P3 (mm)	r2H (mm/d)	r2L (mm/d)
-100	-250	-2000	-8000	-80000	5	1

Where:

PO, is the value of the pore water pressure head h_{w1}, (Figure 15), below which roots start to extract water from the soil.

PO_{pt}, is the value of the pore water pressure head h_{w2}, below which roots start to extract water at the maximum possible rate.

P2H, is the value of the limiting pore water pressure head h_{w3}, below which the roots cannot extract water at the maximum rate (assuming a potential transpiration rate of r2H).

P2L, is the value of the pore water pressure head h_{w3}, below which roots cannot extract water at a maximum rate (assuming a potential transpiration rate of r2L).

P3, is the value of the pore water pressure head h_{w4}, below which root water uptake ceases (usually equal to the wilting point)

r2H, potential transpiration rate (currently set at 5 mm.d^{-1})

r2L, potential transpiration rate (currently set at 1 mm.d^{-1})

The above input parameters permit one to make the variable h_3, a function of the potential transpiration rate T_p (Simunek *et al*, 1999).

$$h_{w3} = \text{P2L for } T_a \leq r2L \, (r2L = 1 \text{ mm.day}^{-1}) \dotfill 4$$

$$h_{w3} = \text{P2H for } T_a \geq r2H \, (r2H = 5 \text{ mm.day}^{-1}) \dotfill 5$$

For the simulated select period in this study T_p was equal 4.2 mm/day and since for r2L$< T_p <$r2H,

$$h_{w3} = P2H + \frac{P2L - P2H}{r2H - r2L}(r2H - T_p) \text{ then } h_3 = -3200 \text{mm} \dotfill 6$$

As explained in sections 2.4.4, 2.4.5 and 2.4.6, the sink term, s represents the volume of water removed per unit time from a unit volume of soil due to plant water uptake. s is defined as

$$s(h_w) = a(h_w)s_p \text{ (Simunek } et al, 1999) \dotfill 7$$

where:

a(h_w) is a prescribed dimensionless function of the soil water pressure head ($0 \leq a \leq 1$),

s_p is a potential water uptake rate.

Figure 15 gives a schematic plot of the stress response function as used by Feddes, Kowalik and Zaradny (1978) cited in Simunek *et al.*, 1999. When the potential water uptake rate is equally distributed over a two dimensional rectangular root domain (Figure 16), s_p becomes:

$$s_p = \frac{1}{L_x L_z} L_t T_p \dotfill 8$$

where: T_p is the potential transpiration rate (L.T^{-1}),

L_z is the depth of the root zone,

L_x is the width (L) of the root zone and

L_t is the width (L) of the soil surface associated with the transpiration process.

By introducing a nonuniform distribution of the potential water uptake rate over a root zone of arbitrary shape,

$$s_p = b(x,z) L_t T_p \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots9$$

where:

$b(x,z)$ is the normalized water uptake distribution (L^{-2})(Simunek *et al*, 1999).
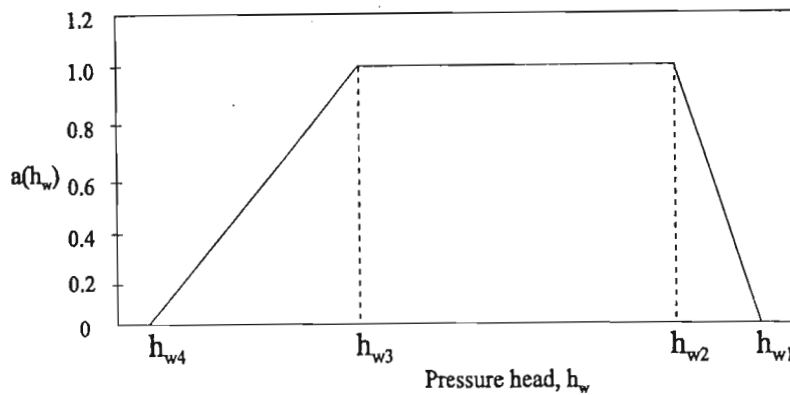
Figure 15   Schematic diagram of the plant water stress response function a(h), as used by Feddes *et al*, 1978 cited in Simunek *et al.,* 1999

This function describes the spatial variation of the potential extraction term, s_p, over the root -zone. The actual water uptake distribution is given by:

$$S(h,x,z) = a(h,x,z)b(x,z)L_t T_p \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots10$$

Details on the derivation of this equation can be found in Simunek *et al*, 1999.

3.5.3   Atmospheric information

The atmospheric boundary conditions were supplied via the input file ATMOSPH.IN, shown in Appendices H and I, for Willowfontein and Taylors Halt respectively. The variables, given in the ATMOSPH.IN file, are:

hCritS - Maximum allowed pressure head at the soil surface (mm),

tAtm(i) - Time for which the ith data recorded is provided (min),

Prec(i) - Precipitation $(mm.min^{-1})$,

rSoil(i)   - Potential evaporation rate $(mm.min^{-1})$,

rRoot(i)   - Potential transpiration rate (mm.min^{-1}),

hCritA(i)   - Absolute value of the minimum allowed pressure head at the soil surface,

rGWL(i)/rt - Drainage flux (mm.min^{-1}) across the bottom boundary or other time dependent prescribed flux boundary condition and

GWL(i)/ht - Ground water level (mm),usually negative, or other time dependent prescribed boundary condition
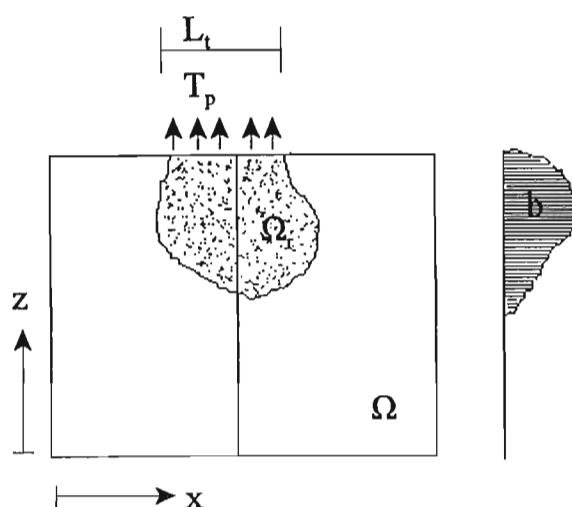
Figure 16   Schematic diagram of the potential water uptake distribution function, b(x,z) in the root zone after Simunek *et al*, 1999

Note that no rainfall was recorded at Willowfontein for the select periods. Therefore no rainfall data appear in the ATMOSPH.IN file, except that the time dependent pressure head (GWL/ht) in the irrigation zone was specified (Appendix H). Rainfall was recorded at Taylors Halt for the selected period, as can be seen in Appendix I. Owing to the difficulty of combining the atmospheric boundary conditions with time-dependent pressure heads in simulating hand irrigation at Taylors Halt, irrigation amounts were included as precipitation amounts on the days without rainfall but which were recorded as irrigation days. Therefore, no time dependent pressure heads were required to be specified for the Taylors Halt site. Examples of output files are given in Appendices J and K for Willowfontein and Taylors Halt respectively.

4. RESULTS

4.1   Social System Appraisal

4.1.1   Willowfontein

4.1.1.1   Overview of the community gardening group at Willowfontein

The name of the gardening group at Willowfontein is Sizanani number I . Sizanani means a collection of people working as a unit towards achieving a common goal. It was named Sizanani number I since there was another group that was to be formed and which was to pursue similar objectives. This group was to be called Sizanani number II. At the time of conducting this study, Sizanani number II was not operational, but was going to be allocated the same size plot as Sizanani number I, elsewhere in Willowfontein . Sizanani number I's main aim was to grow vegetables for consumption by their families and to sell some to augment family income. The group members having felt the scourge of unemployment, realised they had to do something to improve their lot, hence the formation of this gardening group.

Sizanani number I consisted of twenty five members i.e. four males and twenty one females. The small number of males actively involved in this group was indicative of the perception that men regarded agricultural work to be women's work The group activities were managed by a Management Committee whose structure consisted of the Chairperson, the Vice Chairperson, the Secretary, the Vice Secretary and a Treasurer. This Management Committee met regularly to discuss issues pertaining to land preparation, purchasing of seeds and fertilizers prior to the start of the next season and various other pertinent issues. At these meetings minutes were taken in order to keep records of matters agreed upon and to keep track of what was achieved and what still needed to be achieved.

The group had a constitution which guided the activities of the members. It was enshrined in this constitution that each member joining the group should contribute an amount of twenty rands, which was regarded as a joining fee. Subsequent to that, an amount of ten rands was paid by each member on a monthly basis. All contributions made by the members were deposited into the group's banking account. Funds in this account were utilised for hiring the tractor to do land

preparation, to purchase seeds, fertilizers, pesticides, to cover transport costs and for the general maintenance of the garden.

Since the formation of this agricultural project, cultivators at Willowfontein had always regarded strategic partnerships and linkages with other organisations and institutions having interest in small scale agricultural activities as highly valuable and critical to their success. These partnerships include the Department of Agriculture, Institute of Natural Resources, Greater Edendale Environmental Network and Kwa-Nalu farmers union. Group members maintained that being members of the Kwa-Nalu farmers union was beneficial in many ways. To mention a few, they received discounts on seeds from NCD, a deal negotiated by the union officials on behalf of the farmers; they could apply for loans from the Land Bank and they have used the Kwa-Nalu office as their reference. The Department of Agriculture has provided them with extension services, and a tractor during land preparation and transportation. Group members were grateful that the Department was providing such assistance and hoped that the frequency and reliability would improve.

4.1.1.2   Land ownership and land tenure at Willowfontein

Although land at Willowfontein belonged to the Pietermaritzburg Transitional Local Council (TLC), land allocation to community activities was conducted by the Willowfontein Development Committee. Land currently utilized by the Willowfontein gardening group (Sizanani number I) was allocated to them by this Committee. It was land that was reserved for a cemetery, but was not utilised for that purpose when this study was conducted, and it was for that reason that there were no dwellings within the immediate surroundings of the agricultural plot. Presently, the members of the gardening group do not contribute anything for land and do not have any formal tenure arrangement in place.

4.1.1.3   Garden layout, participation and irrigation at Willowfontein.

An area of about 0.7 ha was fenced. This area was subdivided into subplots of approximately 28 m x 10 m and each subplot belonged to an individual member of the group. At a distance of approximately 200 m from the South East corner of the fence surrounding the plot was a small farm dam (Figure 2). Previously, this dam belonged to a farmer who practiced stock farming as one of his farming activities, and water from this dam provided drinking water for stock. A water

supply channel was constructed from this dam into the irrigated vegetable garden. Water from the dam was directed along a constructed channel into the garden during irrigation. This channel was at the top part of the garden and ran parallel to the fence at the toe section of the garden. An in-field main channel intersected the water supply channel. During irrigation, water was diverted along the furrows from this in-field main channel to irrigate the various sub-plots according to the irrigation requirements of the irrigators. Excess water running on the water supply channel was led off into the small stream on the west side of the garden.

The garden committee was responsible for the allocation of sub-plots to members of the group. There were no rules governing allocation of sub-plots, as such there was no existing criteria as to who should be allocated a sub-plot at the top part of the garden closer to the water supply channel, or near the fence at the toe part of the garden, which was quite removed from the water supply channel. Allocation of sub-plots was done at random. Observations made during the course of carrying out this study, were that some sub-plots were left fallow for the entire season. The reason for this was that some members gave up participation in the gardening activity for better employment elsewhere, and since the gardening group committee did not enjoy sufficient powers to decide on abandoned sub-plots, these sub-plots were left unattended for a long time. The Willowfontein Development Committee was the body with sufficient powers to resolve matters such as abandoned sub-plots and given their pre-occupation with other developmental work in the area, they did not attend to the issue of abandoned sub-plots swiftly. The project management committee could not resolve such issues.

At Willowfontein, some members had their sub-plots closer to the water supply channel, while others had theirs at a distance from the main channel. During low flows i.e. in winter, the distance of the cultivators sub-plot from the water supply channel significantly influenced irrigation efficiency. This was because during low flows, the amount of irrigation water delivered at the toe part of the garden was considerably less than that delivered to sub-plots closer to the main channel at the top part of the garden. This had been a source of dispute between irrigators and after a series of disputes over irrigation water during the winter season, the cultivators realised the need for a solution to this problem of uneven distribution of water during the winter season. To resolve these recurrent conflicts an agreement was reached between cultivators on the general principle that water be allocated on a first come first served basis. This

principle of water allocation eliminated the advantage that some cultivators enjoyed over others. This allowed rotation of water use among the cultivators as early arrivers on the day would not bother to be early arrivers on the next day. Over time a decision was made to adopt this rotational system based on early arrival at the field for both summer and winter seasons. The difference being that with the abundance of water in summer, more than two cultivators irrigated at any one time, whereas in winter a maximum of only two cultivators irrigated at one time. When this study was carried out, cultivators at Willowfontein were not aware of any upstream or downstream users except that the dam was also a source of drinking water for stock that belonged to some community members.

Cultivators at Willowfontein did not experience severe water shortages throughout the year, therefore there were no plans of either storing or harvesting water during the rainy summer season. An interesting observation they highlighted to the postgraduate researcher was that after a low intensity rainfall event lasting for a maximum of approximately six hours, crops showed more life than would be the case after an irrigation event. Their explanation for this was that during such a rainfall event crops received sufficient water covering the entire root zone, they added that that was not the case with their furrow irrigation system, which had to last for a relatively short period to prevent crops stressing as a result of water logging. This observation made cultivators aspire to install water pipes and sprinklers as one of their immediate plans should they secure funding. They believed that the installation of such a system would increase water application efficiencies, relative to transmission losses currently experienced from the water supply and in-field main channels. This belief was verified as indicated in the monitored results in section 4.2.2.1.1

4.1.1.4 Constraints to the development of the community gardening activity at Willowfontein

At the time of conducting this study, the Willowfontein cultivators concentrated on growing vegetables and not staple foods. They feared that growing staple crops like maize would lead to increased levels of crop theft. Although they experienced theft of produce from the vegetable garden the problem was not as severe as they anticipated it would be with staple crops. To grow staples, the growers would need to ensure that there were proper security mechanisms in place to guard against theft. They explained that thieves found it easy to sell staples like maize as

opposed to vegetables. The lack of management skills required to manage a communal type project was realised as a serious hindrance to their development. Other serious constraints to the development of their gardening activity related to the lack of training and support on good agronomic practices. Although they were receiving some assistance from the Department of Agriculture in the form of extension services, they felt they needed consistent support on good agronomic practices such as crop production, vegetable production, appropriate irrigation technologies and maintenance of such technologies, optimum irrigation strategies and advice on which crops/vegetables were suitable for their area. The cultivators pointed out that they would like to strengthen their organisational formation. To achieve this they believed that training on organisational development, conflict resolution and management would be most appropriate. During the course of carrying out this study, it became evident that the cultivators had no idea of how much profit they were making from the sale of their produce, save to say that they were quite confident that they were not suffering from loses. This was judged against what they would contribute towards vegetable production and the benefits thereof. There is an obvious need to educate these growers in the area of basic bookkeeping and costing.

4.1.1.5   Sale of garden produce

Cultivators sold their produce to the local shops and to individual members of their community. They could not sell outside their community, the main cause of this was the unavailability of transport of their own and hiring transport became a costly exercise. The cultivators' hope was to get transport of their own at some stage as well as to establish a local fruits and vegetables market that they would supply with produce from their garden. They believed that an establishment like a community market, would go a long way towards alleviating some of the problems they experienced with local shop owners. These local shop owners dictated the price to them, something they found unacceptable. When this study was conducted, the Willowfontein cultivators had not received any form of financial support. Whilst they would really appreciate financial support, they thought they would use it to secure training on financial management so as to ensure that finances were managed properly for the sustainability of the project.

4.1.2 Taylors Halt

4.1.2.1 Overview of the Taylors Halt group

The Taylors Halt group is called Nhlanhleni farmers. Nhlanhleni means the lucky ones. This group named itself Nhlanhleni farmers since members considered themselves to have been lucky to obtain land they could utilize for their agricultural project. Like the Willowfontein group, this Taylors Halt group, once it was formed, had the production of vegetables for sale and for consumption by their families as its primary aim. To date, they are also engaged in poultry farming.

Nhlanhleni farmers group consisted of eighteen members, sixteen females and two males. Again, the small number of male participation in this group was also attributed to the perception of gardening work being women's work. The operations of the group were managed by a Management Committee whose structure consisted of a chairperson, a vice chairperson, a secretary, a vice secretary, a treasurer and two additional members. This group met regularly on Monday mornings to discuss issues relevant to their agricultural project and other farming activities. At each meeting, minutes of the meeting were taken so as to keep track of events and decisions taken. A person joining the group for the first time had to pay a joining fee of one hundred rand, subsequently he/she was expected to make monthly contributions of five rand. Although the hundred rand could not be recovered in physical cash from the sale of one season's produce, the value of vegetables harvested in one season exceeded one hundred rand. Some of the vegetables were consumed by their families and some set aside for sale. According to the group members the contributions were important in order to cover the maintenance and running costs of the agricultural project, excluding the purchase of seed and fertilizers. Cultivators made separate contributions towards the purchase of seed, seedlings and fertilizers from revenue generated from the sale of their produce. The joining fee plus the monthly contributions were deposited into the group's banking account. The postgraduate researcher noticed collective commitment among the group members to accumulate funds in their banking account so as to advance their current agricultural activity or to develop other farming activities. The reason why new members had to pay a joining fee of one hundred rand was that, when a community garden was initially setup there were inherent costs which were taken care of by the members at that time e.g. fencing and maintenance of the fence around the garden. New entrants to the gardening

group were therefore expected to contribute towards these costs.

The guiding document of the Nhlanhleni group was their constitution. This constitution was drafted and adopted by the members of the group in collaboration with the extension officers. A copy of this constitution was given to each committee member, it was read to each new member that joined the group, and from time to time it was reviewed by the committee members. The chairperson had powers vested upon him/her by the constitution to intervene whenever there was a breach by any of the members.

Although this group valued partnerships or linkages with other organisations pursuing similar objectives, the group had resolved to be cautious as to with whom they associated. This was to a large extent influenced by their past experiences with some organisations which purported to be assisting them, but only to realise, with time, that the organisations were using the group to advance their own aims or objectives.

4.1.2.2 Land ownership and land tenure at Taylors Halt

At Taylors Halt all land belonged to the chief. When this agricultural project was first initiated the local chief was approached with an aim of obtaining land that could be utilized for the agricultural project. The chief applauded the idea and allocated approximately 0.5 ha of land for agricultural use to the Nhlanhleni farmers. It is also worth mentioning that the same chief was approached by the post graduate researcher to seek permission to carry out this research work. The chief mentioned to the postgraduate researcher that he was committed to the development of his people and his area, therefore he would not want to jeopardise activities which aimed to develop them. He then granted permission to carry out this study. Since the cultivators were given land by the chief, they were not expected to make any financial contributions towards the land they used. However, these cultivators did not possess any documentation granting them permission to use the land or tenure. The land allocation and tenure system at Taylors Halt was very informal.

4.1.2.3 Garden layout, participation and irrigation at Taylors Halt.

The Taylors Halt site was a community vegetable garden of approximately 0.5 ha in extent (Figure 3). At the toe part of the vegetable garden located on a north facing hillslope with an

average gradient of 11%, was a non perennial stream which was the source of irrigation water. This stream posed serious irrigation problems in winter when it ran dry. It was for this reason that very little or no gardening activity took place in the dry winter season. The residents in this area were heavily reliant on the produce from the community garden for vegetables. The commitment they displayed and the amount of time and effort they put into their gardening activity was clear evidence of this fact. All the members of the group owned the same size sub-plots, which were of equal length stretching from the stream at the toe of the garden to the top part of the garden. These sub-plots of approximately 28 m x 10 m each, ran parallel to each other, and that position ensured that there were no complaints about other cultivators enjoying shorter distances between their subplots, and the source of irrigation water.

During irrigation, water is collected from the stream using large containers (buckets of approximately 20 L). These are then carried to the irrigated sub-plots and smaller quantities of water are applied from these buckets to the crop. The amount of water applied per crop per irrigation event was approximately 18.0 mm. This estimate was calculated from the volume of the container that was used for irrigating and was divided by the wetted area only. Irrigation when it took place was carried out in the afternoon in summer and early in the morning in winter. In winter, cultivators irrigated early in the morning so as to reduce the effects of frost on crops. There were no rules governing water use and allocation at Taylors Halt, save to say cultivators were expected to irrigate their crops sufficiently i.e. such that they did not show any signs of stress, especially in summer when there was enough water to irrigate. The cultivators pointed out that they have had no conflicts over irrigation water amongst themselves ever since the project was established. They added that this was largely due to the fact that each cultivator collected his/her own water and there was sufficient water for all the members to irrigate during the summer season. At the time of conducting this study, the cultivators had no knowledge of any upstream users but mentioned that downstream users used this water only for non-consumptive domestic purposes such as laundry. The problem of water shortage in winter affected both the irrigators and the domestic users at Taylors Halt. It was precisely to solve this problem of water shortage in winter that cultivators indicated their desire to store or harvest rain water. Stored water would be used for irrigation and other domestic purposes. If funds became available they would also like to install a sprinkler irrigation system. Their preference for the sprinkler irrigation system was based on the understanding that it required less labour than the

bucket type irrigation system currently being used and that with a sprinkler irrigation system, sufficient water would be made available to the crop after each irrigation event.

Observations made by the postgraduate researcher at the Taylors Halt site were that, unlike at Willowfontein, not a single sub-plot was left fallow when others had crops growing on them. Also, the entire plot was uniformly planted. The reason for this uniformity was attributed to the strict rules governing operations of the group and to the strictness of the chairperson who ensured the enforcement of these rules. The chairperson was also regarded by the rest of the members to be the most influential person of the group. Cultivators agreed at their meetings as to which crops to grow, when to irrigate and when to remove weeds. Any member of the group who deviated from the agreements reached, could be expelled from the group. If for some reason a sub-plot was abandoned by its owner, it immediately became the responsibility of the group members to work on that sub-plot collectively, revenue generated from the sale of the produce from that sub-plot was deposited in the group's banking account, and did not accrue to individual members.

4.1.2.4   Constraints to the development of community gardening activity at Taylors Halt

As with the Willowfontein group, the Taylors Halt group had focussed on growing vegetables and not staple crops. They had similar fears as the Willowfontein group, that growing crops like wheat and maize could lead to increased levels of theft. Although they were experiencing theft of vegetables, the problem was not as severe as they anticipated it could be with these other crops. They felt that to grow grain crops they would need proper fencing with a lockable gate and a security guard. Other constraints to development were identified as lack of training and technical support on good agronomic practices. While extension services provided by the Department of Agriculture were essential services that they needed, they felt that dedicated training and technical support on good agronomic practices would compliment the services provided by the Department of Agriculture. Specific areas of training were identified as crop production, vegetable production, appropriate irrigation technology and optimum irrigation strategies. Again, like the Willowfontein group, the Taylors Halt group could not give figures of the profits they were making from the sale of their produce, clear evidence of the need to develop their skills in basic bookkeeping and costing. Although community gardening groups are generally small in size, their management calls for generic business enterprise management skills together with organisation management skills, which are virtually absent in many of these

groups. It is to overcome these constraints to their development that they expressed a strong desire to gain organisation and business management skills. This group also expressed the same desire as the Willowfontein group in terms of strengthening their organisational formation, ie they needed training on organisational development, conflict resolution and management. Like the Willowfontein group, lack of financial administration was also observed with the Taylors Halt group, and these are serious constraints to community groups constantly in search of donor funds.

4.1.2.5   Sale of garden produce

Most of the produce was sold to the nearby shops and to individual community members. The main problem experienced with the sale of produce was the unavailability of transport. Although the extension officer helped with providing transport for the delivery of vegetables to the local shops, this transport was not freely available and as such they could not sell as much as they would have liked to, so growers ended up consuming some produce that they would have otherwise sold to the shops, fruit and vegetable markets and individuals outside their community. Serious frustrations over the inability to sell all the produce set aside for sale were expressed by the group members.

Infrastructural development under small scale agricultural conditions requires an understanding of the social and organisational basis surrounding water use and allocation (Abeyratne, 1990). Therefore, technical system analysis results and recommendations should be made within the context of existing patterns of water allocation and distribution, and the organisational formation of local communities in order to be effective and sustainable in the long term. The following sections analyse the technical system in both the study sites.

4.2   Technical System Analysis

This technical analysis of the system used considers the soil hydraulic properties at both sites, analysis of tensiometer, rainfall, irrigation data, groundwater survey and finally presents the modelled results.

4.2.1   Soil hydraulic properties

Description of soil hydraulic properties with methodologies used in their measurement were outlined in Section 3.4. Section 4.2.1.1 below contains the results of the saturated and unsaturated hydraulic conductivities for both Willowfontein and Taylors Halt experimental sites.

4.2.1.1   Saturated and unsaturated hydraulic conductivities

A total of seven double ring (DR) and sixteen tension infiltrometer (TI) tests were successfully completed in this study.   Shown in Appendices C and E are the hydraulic conductivity characteristics as determined from measured data.   At different depths below the soil surface, double ring and tension infiltrometer tests were carried out.   Unsaturated hydraulic conductivities were established at the surface for each of the nests at the two sites.   Graphical representation of these hydraulic conductivities for each nest at Willowfontein are shown in Figure 17.
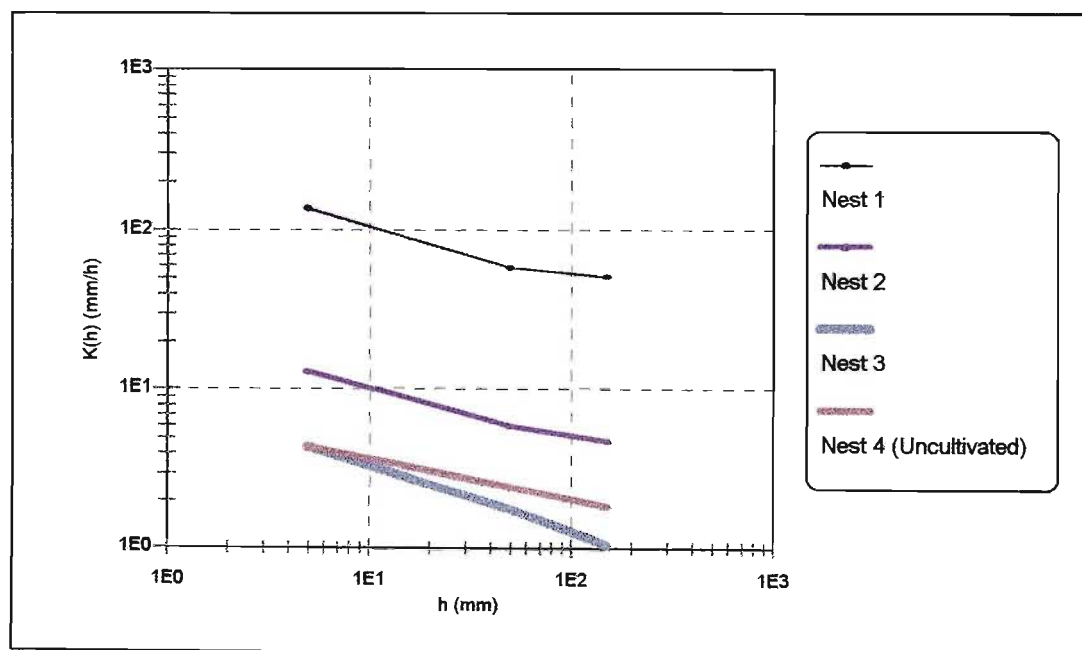
Figure 17   K(h) as a function of Capillary Pressure Head (h) for the soil surface at Willowfontein.

The results show conductivity to be much higher for Nest 1 compared to the rest of the nests, and since these measurements were carried out just after ploughing had been completed at Willowfontein, this difference in conductivity could be attributed to uneven land preparation

resulting in looser structure and hence higher conductivity in the vicinity of Nest 1. Although the physical properties of the soils were not established in this study, it can be said that from observations the surface soils appeared to be similar throughout the entire plot (Loam soil type). Noticeable differences in conductivities established at different depths in the established (near Nest 2) pit are illustrated by Figure 18 and are discussed in the following section.

From Figure 18, it can be seen that hydraulic conductivities differ for different depths down the soil profile. This is likely to be caused by an increase in clay content together with greater compaction or consolidation at the depicted depths. The observable anomaly showing higher conductivities (K(h)) for higher Capillary Pressure Head (CPH) at depths of 300 mm below surface could be attributed to experimental error. Saturated conductivities also suggest differences in the soil textural properties for the corresponding depths, with saturated conductivities also decreasing down the soil profile. Both saturated and unsaturated conductivities established at the Willowfontein site are given in Appendix C.
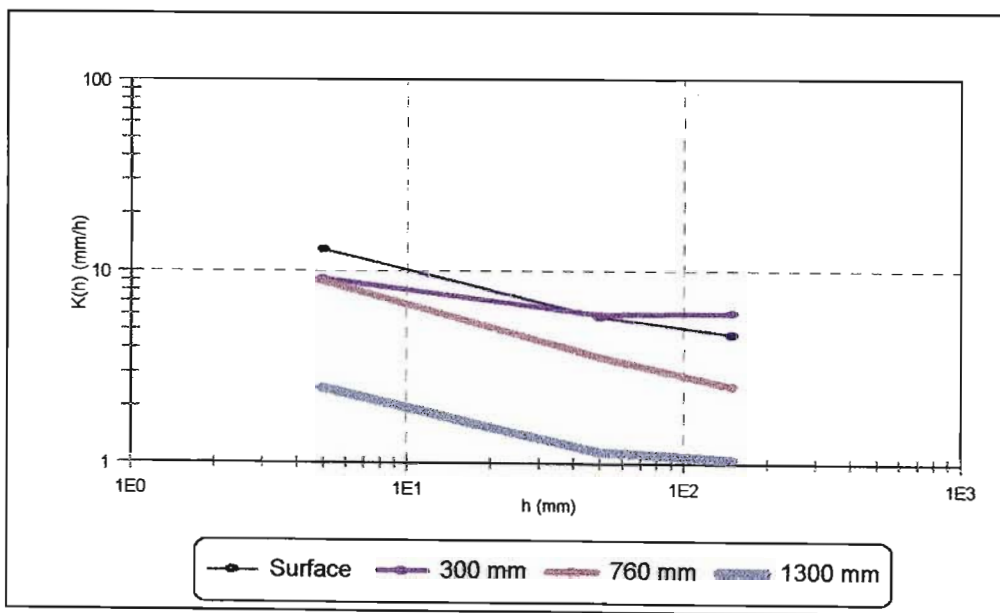
Figure 18   K(h) as a function of Capillary Pressure Head (h) for the pit established at Nest 2 at Willowfontein

The same measurements were carried out at the Taylors Halt site and, unlike at Willowfontein, unsaturated hydraulic conductivities K(h) at the different nests appear to be similar (Figure 19). This shows the uniformity of both the surface layers' textural properties and land preparation

along the transect where the four nests were installed. For the first three Capillary Pressure Heads, K(h) at Nest 1 appears higher than the other nests. This is attributed to the looser structure of the soils resulting in what appears to be higher hydraulic conductivity in the vicinity of Nest 1.

Examination of Figure 20 shows a noticeable decrease in K(h) down the soil profile at Taylors Halt. This is a clear indication of the differences in the physical properties of the soils at the corresponding depths. Surface conductivities K(h) are lower than conductivities at depth 320 mm below surface. Although a bit of surface sealing could possibly be the cause, this appears incorrect since the surface conductivities (Figure 20) are lower than surface conductivities measured independently at Nest 2, yet the pit was established close to Nest 2 (Figure 19). Therefore, this is some indication of the degree of variability of the surface conductivities. However, these differences are not expected to extend into the profile. Saturated conductivities (Ks) decrease down the soil profile which confirms different soil physical properties at corresponding depths.
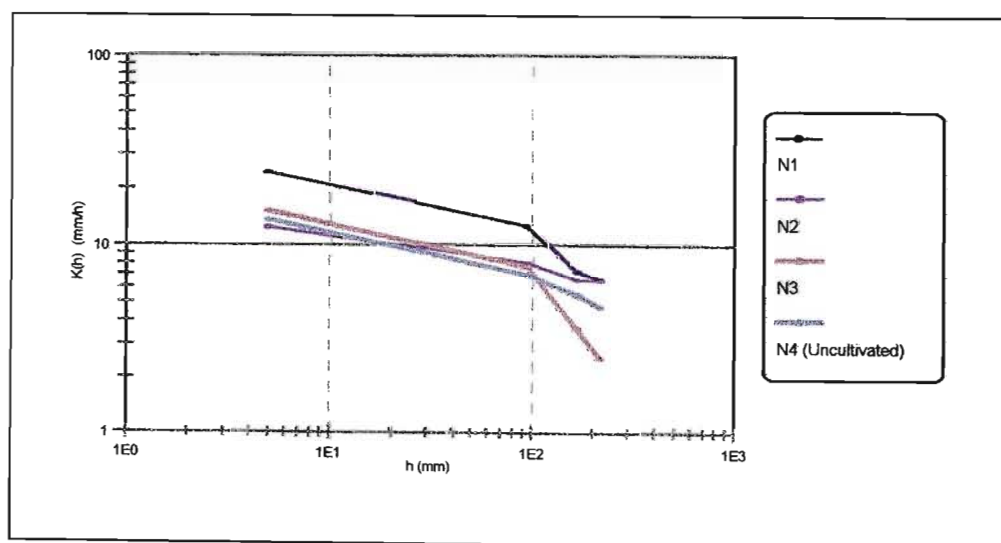
Figure 19   K(h) as a function of Capillary Pressure Head (h) for the soil surface at Taylors Halt
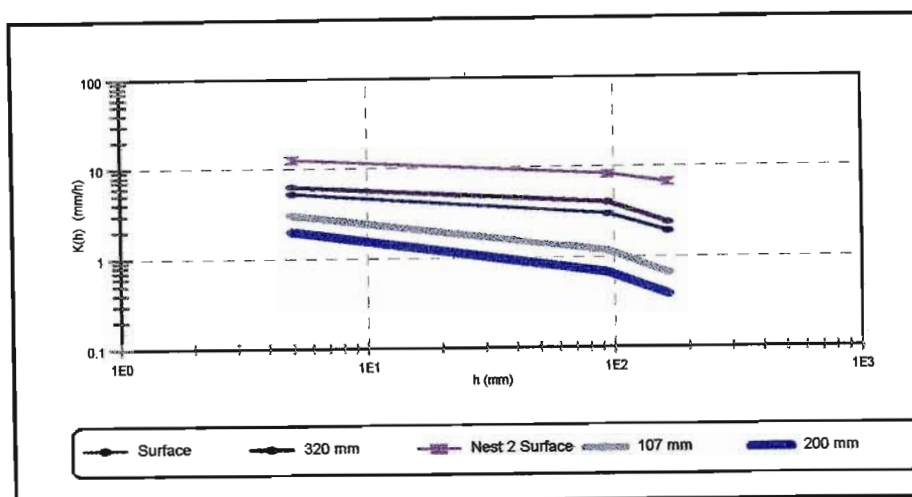
Figure 20   K(h) as a function of Capillary Pressure Head (h) for the established pit nearby Nest 2 at Taylors Halt

Table 6   Unsaturated hydraulic conductivity characteristics at the soil surface for the two sites

Nest	Willowfontein		Taylors Halt	
	CPH (mm)	Unsaturated hydraulic conductivity (mm/h)	CPH (mm)	Unsaturated hydraulic conductivity (mm/h)
2	5	13	5	12
	150	5	215	6
3	5	4	5	15
	150	1	215	2.5
4	5	4	5	13
	150	2	215	5

Comparison of the surface unsaturated conductivities for the two sites in Table 6, for Nests 2, 3 and 4 shows the unsaturated conductivities to be higher for the Taylors Halt site compared to the Willowfontein site. Conductivities shown for each of the nests are for two Capillary Pressure Heads (CPHs) i.e. the lowest and the highest CPH. These differences are attributable to the differences in the physical properties of the soils between the two sites. It is also worth mentioning that for the two sites at lower CPH the conductivities are high suggesting a structurally stable matrix.

Table 7   Saturated conductivities down the soil profile at the two sites

Willowfontein		Taylors Halt	
Depth (mm)	Saturated conductivity (Ks) (mm/h)	Depth (mm)	Saturated conductivity (Ks) (mm/h)
Surface	25	Surface	132
750	13	890	1407
1300	10	1060	8

From the data in Table 6 saturated conductivities (Ks) are expected to be higher for the Taylors Halt site compared to the Willowfontein site. The first two conductivity values given in Table 7 for Taylors Halt appear to be high. Whilst experimental error could not be completely ruled out, the differences between Ks and K(h) for small CPHs at Taylors Halt leads to the conclusion that preferential flow pathways as a result of the proliferation of macropores at the corresponding depths could be the main reason. On the whole, Taylors Halt saturated and unsaturated hydraulic conductivities are higher than those of Willowfontein.

4.2.1.2   Method used to predict hydraulic parameters

Figure 21 illustrates how well the van Genuchten (1980) parameters were used to fit simulated data to observed data for the water retention characteristics. Based on the Maulem (1976) equation (Equation 9) for predicting the relative hydraulic conductivity (Kr) from the knowledge of the soil water retention curve, van Genuchten (1980) derived a closed form equation for predicting the hydraulic conductivity of unsaturated soils, as follows:

$$K_r = \theta^{\frac{1}{2}} \left[\int_0^\theta \frac{1}{h(x)} \partial x \Big/ \int_0^1 \frac{1}{h(x)} \partial x \right]^2 \quad \dots \dots \dots (9)$$

From equation (9) above, h is the pressure head given as a function of the dimensionless effective water content (Se), where

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad \dots \dots \dots (10)$$

and s and r indicate saturated and residual values of the soil water content respectively.
Equation 10 expressed differently can be re-arranged to:

$$\theta = S_e \times \left(\theta_s - \theta_r \right) + \theta_r \dotfill (11)$$

Since van Genuchten (1980) needed an equation relating the water content to the pressure head in order to solve Equation (9) above, the following general equation which is an attractive class of $S_e(h)$ functions was adopted.

$$S_e = \left[\frac{1}{1 + (\alpha h)^n} \right]^m \dotfill (12)$$

Equation 12 expressed differently can be re-arranged to:

$$h = \frac{\left(S_e^{\frac{-1}{m}} - 1 \right)^{\frac{1}{n}}}{\alpha} \dotfill (13)$$

where $\propto$, n and m are van Genuchten (1980) soil water hydraulic parameters.

By imposing certain restrictions upon the values of m and n van Genuchten (1980) then derived the following relative hydraulic conductivity equation.

$$K_r(h) = \frac{\left\{ 1 - (\alpha h)^{n-1} \left[1 + (\alpha h)^n \right]^{-m} \right\}^2}{\left(1 + (\alpha h)^n \right)^{m/2}} \dotfill (14)$$

Since $K(h) = K_s \cdot K_r(h)$ \dotfill (15)

$$\text{then } K(h) = K_s \frac{\left\{1 - (\alpha h)^{n-1}\left[1 + (\alpha h)^n\right]^{-m}\right\}^2}{\left(1 + (\alpha h)^n\right)^{m/2}} \dots\dots(16)$$
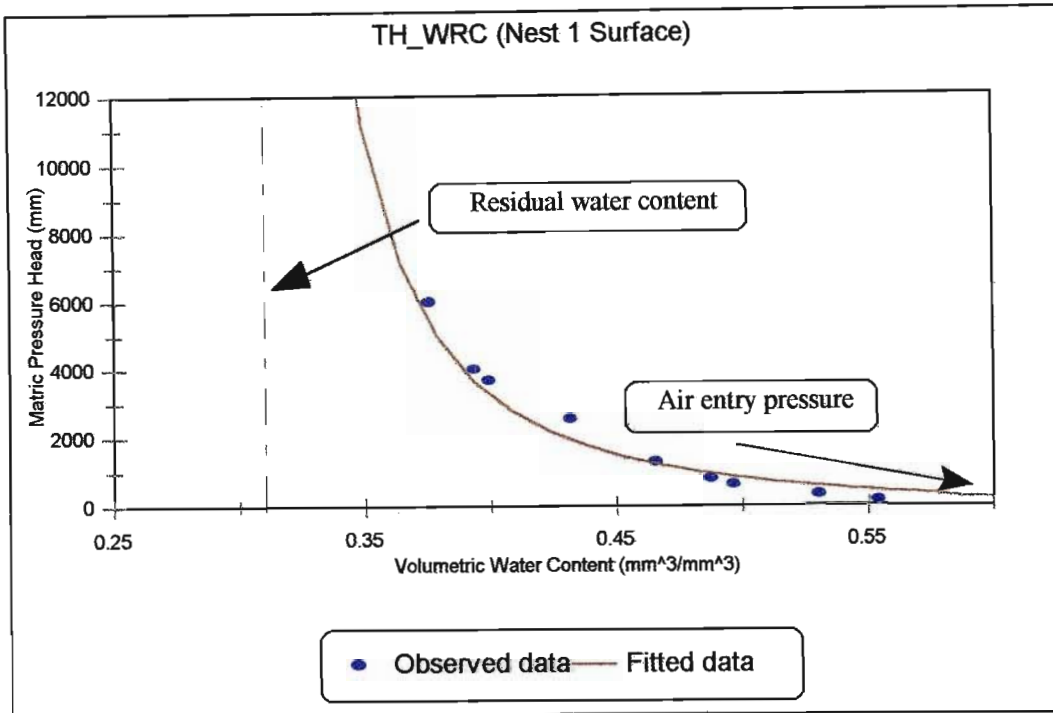
Figure 21   Water retention characteristic for the surface soil at Nest 1 at Taylors Halt, showing observed and fitted data

Details on the derivation of Equation (16) can be found in van Genuchten (1980). In this study the van Genuchten (1980) equations were used to fit the hydraulic conductivity and water retention curves to measured data (Appendix E). Using Equation (11) and Equation (13), water contents and corresponding capillary pressures were optimised against the data for a selected range of S_e as shown in Appendix D. For a selected range of capillary pressures (0.01 mm to 1000 mm), K(h) was fitted to data using Equation (16). The curve fitting procedure used both water retention and hydraulic conductivity data sets simultaneously. Curves were fitted to the data by adjusting θ_r , n, α and m according to the method of van Genuchten (1980). This procedure was carried out on each of the hydraulic conductivity and the water retention curve data derived from the soil samples from each of the pits. The van Genuchten (1980) parameters obtained are presented in Tables 8 and 9 for Willowfontein and Taylors Halt, respectively. An

example of the water retention characteristic curve fitting procedure and fitted curves using van Genuchten (1980) method are given in Appendices D and E, respectively. Using this method the soil water hydraulic parameters used during the modelling exercise were determined, and are given in Tables 3 and 4 for Willowfontein and Taylors Halt, respectively.

Table 8   Willowfontein soil water hydraulic parameters derived using van Genuchten (1980) curve fitting procedure

Willowfontein Pit	n	m	$\propto$ (mm^{-1})	Θ_s	Θ_r
Surface	1.8	0.4444	0.0050	0.497	0.310
Depth = 300 mm	2.0	0.5000	0.0040	0.443	0.297
Depth = 750 mm	1.7	0.4118	0.0039	0.443	0.280
Depth = 1240 mm	1.32	0.2424	0.0090	0.443	0.297

Table 9   Taylors Halt soil water hydraulic parameters derived using van Genuchten (1980) curve fitting procedure

Taylors Halt Pit	n	m	$\propto$ (mm^{-1})	Θ_s	Θ_r
Surface	1.5	0.3333	0.0035	0.661	0.290
Depth = 890 mm	1.4	0.2857	0.0019	0.721	0.300
Depth = 1060 mm	1.4	0.2857	0.0030	0.609	0.200

4.2.1.3   Porosities and bulk densities calculated during the controlled outflow cell analysis

The bulk densities (ρ_b) and porosities (φ) of the soils were determined for each of the samples taken at two depths down the soil profile at each of the sites. Bulk densities (ρ_b) from the Willowfontein site are higher than those from the Taylors Halt site. The bulk densities at both sites increase down the soil profile. This could possibly be attributed to increased compaction at different depths down the soil profile.

Table 10 Willowfontein and Taylors Halt bulk densities determined at three depths below surface.

Willowfontein			Taylors Halt		
Surface	(φ)	0.497	Surface	(φ)	0.661
	(ρ_b)	1332 kg/m^3		(ρ_b)	1044 kg/m^3
760 mm	(φ)	0.443	890 mm	(φ)	0.721
	(ρ_b)	1477 kg/m^3		(ρ_b)	1108 kg/m^3
1300 mm	(φ)	0.403	1060 mm	(φ)	0.541
	(ρ_b)	1583 kg/m^3		(ρ_b)	1218 kg/m^3

4.2.2 Monitored Results

Details of the methodology used in monitoring the capillary pressure head, irrigation events, rainfall and groundwater is outlined in Section 3.4. This section considers tensiometer, irrigation, rainfall and groundwater results, since each is related as a result of the various process interactions.

4.2.2.1 Automatically and manually monitored results

In this study, the automatic monitoring of a total of eight tensiometer nests conducted during August 1998 to December 1998 and December 1998 to April 1999 for Willowfontein and Taylors Halt respectively. The predominant breakdown in tensiometer measurements was related either to cracked ceramics cups, air entry into the tensiometer in the connections of the pressure transducer, or as a result of the soils being too dry and air entered into the tensiometer water column through the dry ceramic cup. These incorrect data are easily distinguishable as discontinuous gaps in the data sets and have been discarded (see Appendix F).

As described in section 2.4.4 above, field tensiometry is used to estimate the energy status of soil water. This is achieved through measuring the Capillary Pressure Head (CPH) at the ceramic tip, which reflects the CPH within the soil. A large positive value of CPH compared with a smaller positive value indicates a drier soil in comparison to the soil with a lower CPH. In this instance water will tend to move in the direction of the higher CPH (drier soil) and in response to gravity.

Some aspects of the monitoring system are noted before discussing the monitored tensiometer, rainfall and irrigation results for both sites:

▸   Rainfall data at Willowfontein were recorded as from the beginning of October 1998, and tensiometer data recorded before October 1998 does not have accompanying rainfall data recorded at the site. The rainfall data presented were from a nearby station (approximately 20 km away) and may not be truly representative of the rainfall received at the actual site.

▸   Since for each nest, tensiometer data were recorded at three different depths, data that does not appear in Appendix F were discarded as they were faulty.

▸   For the Willowfontein site the symbol (○) represents only the timing of the irrigation event in the furrows recorded by cultivators and not the amount of water applied, but for the Taylors Halt site this symbol represents both the timing of the manual irrigation event and the amount of water applied per irrigation event and can be read on the cummulative rainfall axis.

▸   Tensiometer nests referred to in Figures 22, 23, 24, 26 and 27 were installed in different sub-plots along a transect and are discussed in Sections 4.2.2.1.1 & 4.2.2.1.2. At Willowfontein, Nest 1 and Nest 2 were installed on sub-plots that belonged to a single cultivator and nest 3 was in a sub-plot cultivated by a different person. It is important to highlight this fact because analysis of the data presented in the subsequent sections is reflective of the cultivator's irrigation habits. However, at Taylors Halt sub-plots were arranged in parallel transects from the top to the toe of the garden, as such all three nests were installed in a transect that belonged to a single cultivator. At both sites nest 4 (the control) was installed outside the ploughed land in the veld (Section 3.3.2.2).

It is important to understand the soil water response to wetting events including current irrigation practices in order to be able to devise protocols for the efficient use of water during irrigation. To achieve this purpose, analysis of both Willowfontein and Taylors Halt tensiometer, rainfall and irrigation data was carried out in this study.

4.2.2.1.1   Analysis of Willowfontein tensiometer, rainfall and irrigation data

To analyse the soil water response to wetting events, tensiometer, rainfall and irrigation data

have been analysed. Typical data sets are presented in Figures 22, 23, 24 and 25. A selected period from 16-10-98 to 20-11-98 was a relatively dry one and resulted in many irrigation events. This is shown by the intermittent increase in Capillary Pressure Head (CPH)[1] which occurred after tensiometer had been replenished with de-aired water, followed with sudden drop in apparent CPH as a result of the soil water suction exceeding the capacity of the tensiometer ceramic. This is caused by the surrounding dry soil at the ceramic tip drawing the water out of the ceramic and allowing air bubbles to enter the tensiometer. This then causes the recorded drop in CPH (Figure 25).

Examination of the Willowfontein data (Figures 22 & 23), shows that rainfall event A did not result in an associated decrease in the capillary pressure head for all three tensiometers. Essentially, this means that the wetting front did not reach the ceramic tips of all three tensiometers to cause a decrease in the capillary pressure head. This also indicates that water from this rainfall event was insufficient to cover the entire root zone of the crops, and since most of the roots were found at depths of approximately 0.19 m below surface, this observation prompted the cultivator of the sub-plot where nest 2 was contained to irrigate, hence irrigation event B. Unlike rainfall event A (Figures 22 & 23), rainfall event M (Appendix F, Figures F1, F2, F3 & F4) shows that this event resulted in an associated decrease in the capillary pressure head for all three tensiometers with final capillary pressures near zero, which indicates near saturated conditions.

Events B, C, D and E (Figures 22 & 23) are all irrigation events. This is illustrated by noting that only very small amounts of rainfall were recorded between rainfall events A and F. In addition, events C and D were recorded by the cultivators as irrigation events. All four events i.e. B, C, D and E resulted in corresponding decreases in the CPH for all four tensiometers, with final CPH near zero, again indicating near saturated conditions. Of significance are the intervals between irrigation events, (ie cycle times) as a result of the different irrigation scheduling practices of the different growers.

The cultivator of the sub-plot containing Nest 1 and Nest 2 irrigated on the 21-10-98 at 1:24 PM

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[1]Note: Capillary Pressure Head (CPH) represent the soil water CPH as a positive quantity

(Event B, Figures 22 & 23). The cultivator of the two sub-plots irrigated again on the 27-10-98 at 1:36 PM (Event C, Figures 22 & 23). On these two occasions the cultivator irrigated both sub-plots, allowing water to flow along the furrow for approximately 30 minutes on the first occasion. On the second occasion, the cultivator irrigated the sub-plot containing Nest 1 for approximately 30 minutes again, but only allowed water to flow along the furrow with Nest 2 for approximately 15 minutes, i.e. half of the time that was spent irrigating sub-plot containing Nest 1. This is clear demonstration of the uneven application of water by any one cultivator responsible for cultivating two sub-plots on which crops are grown. Observations made by the post-graduate researcher during the course of carrying out on-site experimentation were that the cultivators' irrigation patterns were to a large degree influenced by the quality of the crops grown on the sub-plot. Cultivators would spend less time irrigating sub-plots with poor quality crops. Conversely, regular and even water applications were observed on sub-plots with good quality crops. The next irrigation event, after event C was event D (Figure 23). On this day (03-11-98 at 12:12 PM), the cultivator did not irrigate the sub-plot containing Nest 1 (Figure 22) at all, whereas on the 10-11-98 at 12:49 PM, the cultivator irrigated the sub-plot containing Nest 2 for approximately 10 minutes. Some time later, at 1:33 PM, the cultivator allowed water to flow along the furrow next to Nest 1 for approximately 60 minutes (Event E, Figure 22).

Since the cultivator had not irrigated the sub-plot containing Nest 1 for about 13 days, she was motivated to irrigate for a long period during irrigation event E (Figure 22). In Nest 2, the irrigation interval between events B and C was five days, and event C took place on the 6th day (Figure 23). The interval between events C and D was five days and, again event D was carried out on the 6th day. The interval between events D and E was six days and irrigation event E occurred on the 7th day, lasting for approximately 10 minutes. Since this last event was so short, the shallower depth tensiometer (Figure 23, 0.19 m) recorded the smallest drop in CPH of the entire data set indicating a quick drying of the surface soil, following the few millimetres of water which infiltrated the soil during this short irrigation. This is further demonstration of the inconsistency of water application by the cultivators during irrigation as well as the irregular intervals between irrigation events. This can be construed to be poor irrigation scheduling by the cultivators at Willowfontein.

A different cultivator was responsible for the irrigation of the sub-plot containing Nest 3. In figure 24, event G is an irrigation event that was carried out on the 02-11-98 at 5:55 PM. It was on that same day that the shallower depth tensiometer (0.19 m) had lost CPH as a result of the surface soil layer being too dry, drawing the water out of the ceramic and allowing air bubbles to enter the tensiometer. The high CPH was recorded after the tensiometers had been replenished with de-aerated water. Label H illustrates a drop in CPH of the shallower depth tensiometer (0,19 m) as a result of the soil being too dry which occurred a few days before the cultivator could irrigate again as shown by the irrigation event I (Figure 24). This phenomenon is illustrated by the sudden increase in CPH of Nest 4 tensiometers following replenishment (Figure 25). The interval between irrigation event G and I was eleven days. Irrigation event G and I lasted for approximately 40 and 30 minutes respectively, with event G taking place on the 02-11-98 (11:00 Am) and I on the 12-11-98 (10:08 Am).

Figure 22   Nest 1, Willowfontein tensiometer, rainfall and irrigation data
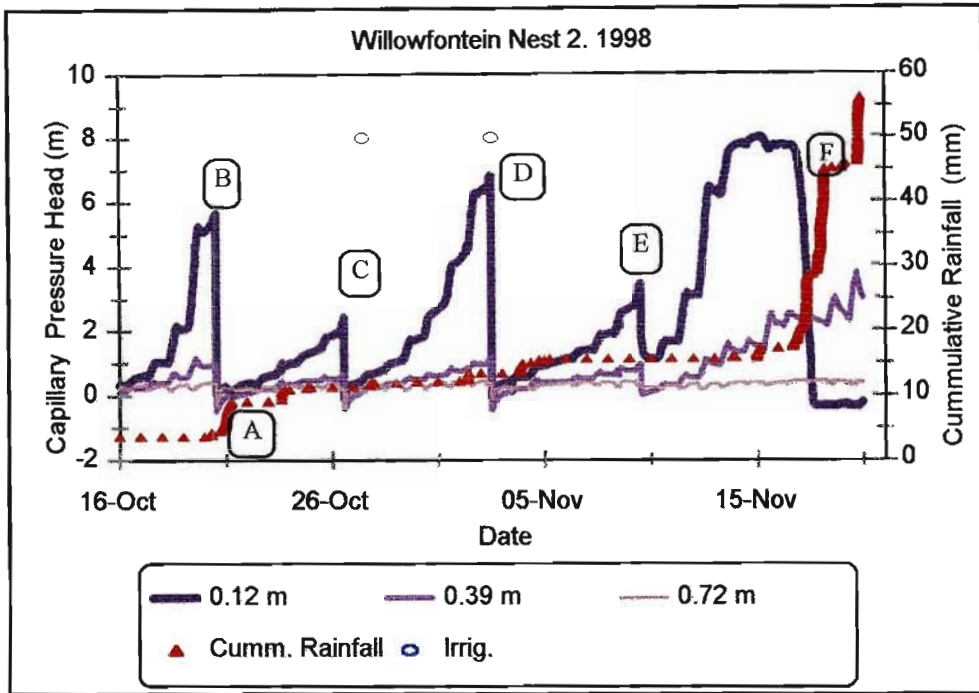
Figure 23   Nest 2, Willowfontein tensiometer, rainfall and irrigation data
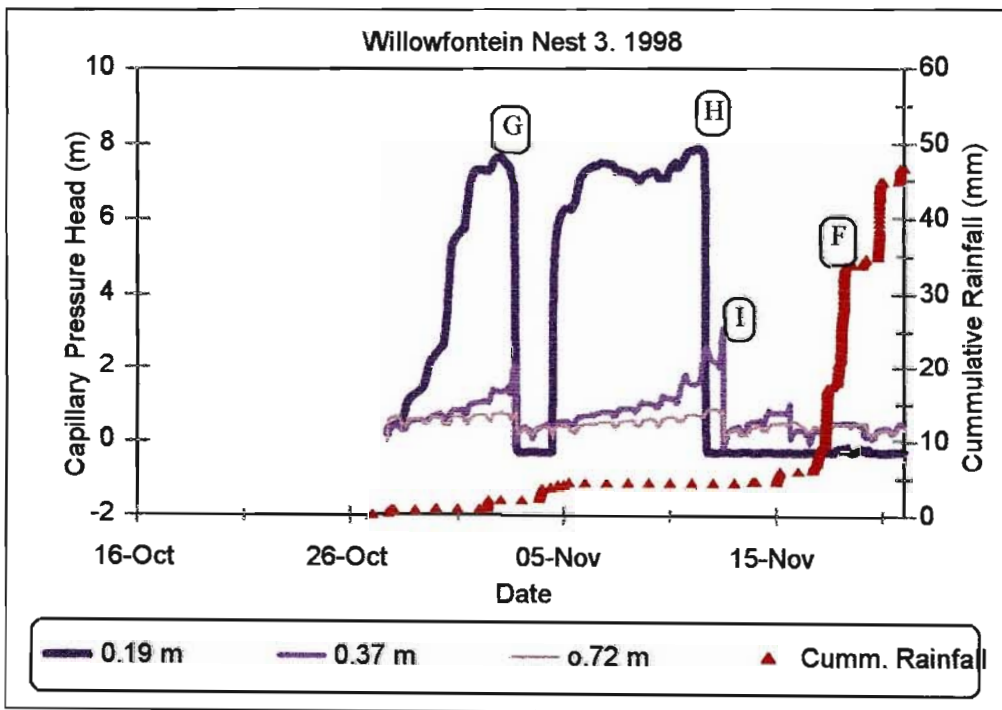
Figure 24   Nest 3, Willowfontein tensiometer and rainfall data
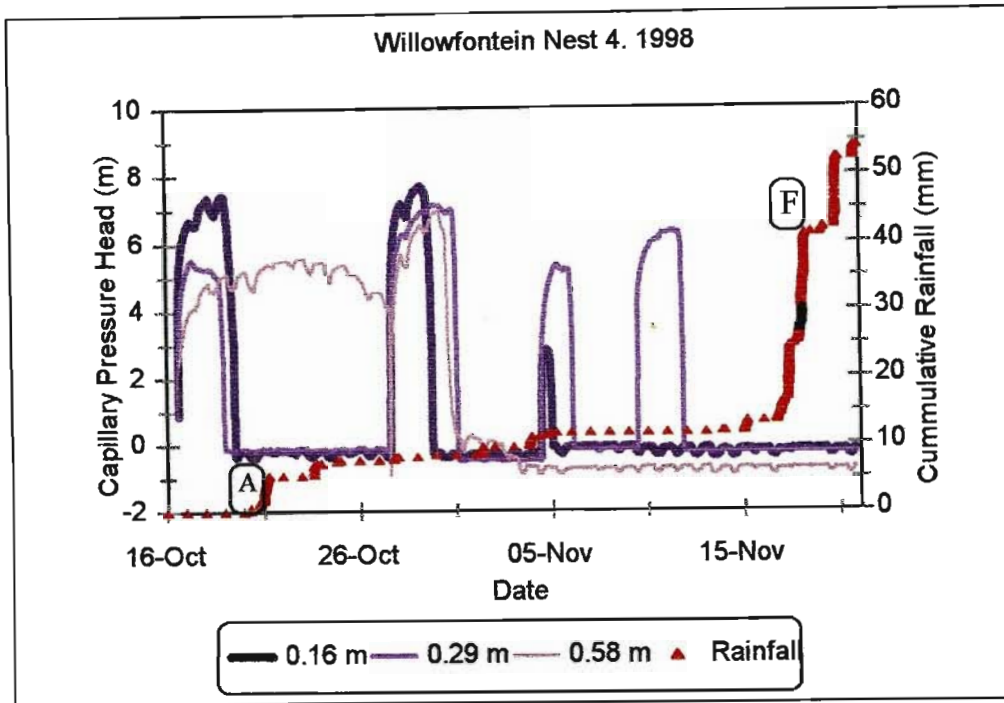
Figure 25   Nest 4, Willowfontein tensiometer and rainfall data

From the analysis of Nest 3 data it can be concluded that the cultivator of the sub-plot containing this nest allowed more time to elapse before irrigating again compared to the cultivator of sub-plots containing nests 1 and 2. These differences in irrigation timing of the different cultivators culminate from the freedom that cultivators enjoy in determining their own irrigation patterns at Willowfontein.

For the rainy season careful examination of the good patches of data presented in Appendix F, show a drop in the CPH as a result of rainfall wetting events (Figure F5, Block A). According to the observations by the post graduate researcher, no supplementary irrigation was carried out by the cultivators during the wet December month, and a total of 135.4 mm of rainfall was recorded for that month.

4.2.2.1.2   Analysis of Taylors Halt tensiometer, rainfall and irrigation data
The entire period monitored at Taylors Halt was a relatively wet period (Dec.1998 - April. 1999), and to assess the soil water response to wetting events at the Taylors Halt site selected tensiometer, rainfall and irrigation data typical of the entire period are presented in Figures 26, 27 and 28.   Examination of nest 1 data (Figure 26) shows that rainfall event J resulted in a

corresponding decrease in the capillary pressure head of all three tensiometers, with final capillary pressure near zero which indicates near saturated conditions at depths to 0.72 m.

Nests 1 and 2 data do not indicate any tensiometer response to irrigation water applied (Figures 26 & 27). This was the case for the entire period monitored and is especially noticeable over the period of daily applications between the 25th and the 31st of March 1999, where no significant wetting is evident, even at 0.2 m below surface (Figure 27). The amount of water applied locally to the crop during irrigation was about 18.0 mm per event. However, the frequency of irrigation was mostly on a daily basis as is shown in the select period (Figures 26 & 27). Diurnal fluctuations predominant in the selected data set should not be mistaken for changes in the CPH as a result of irrigation events. These fluctuations are due to temperature changes affecting small air bubbles in the tensiometer water. Irrigation event K show instances where cultivators irrigated despite the soil CPH being lower than 1 m, meaning that all three soil depths were wet and water applied would have been excess water that would drain to the deeper soil layers (Figures 26 & 27).

In the control nest where no irrigation took place (Figure 28), at 0.57 m below surface, the CPH was between 1 and 2 m before event K was carried out (Figure 26) and a few days after event K indicating acceptable moisture conditions, without irrigation event K.

Comparison of the three nests for the selected periods (Figures 26, 27 and 28) shows that, after the 23rd of March, supplementary irrigation in Nest 1 and Nest 2 resulted in those plots being wetter than Nest 4. Although Nest1 and Nest 2 (Figures 26 and 27) were installed on two separate sub-plots, it is quite evident from the data that both sub-plots were irrigated whenever the cultivator was irrigating and that approximately the same amount of water was applied locally to the crop through the use of the bucket irrigation system (Section 3.2.1.3).

4.2.2.1.3 Piezometers

Piezometer access tubes were installed next to each tensiometer nest. Details of installation, the groundwater monitoring procedure and groundwater survey carried out at Taylors Halt are given in section 3.4.1.8. Presented below are the groundwater monitoring and survey results at the corresponding depth in each nest.

4.2.2.1.3.1 Willowfontein site

At this site the piezometer access tubes were installed at the end of August 1998. At Nest 1, the piezometer hole was augured to a depth of 1235 mm, but no groundwater was recorded during the entire monitoring period. Similarly, in Nest 2 with a piezometer hole of 1895 mm below the surface, no groundwater was recorded throughout the monitoring period. The piezometer access tube installed at Nest 3, was the closest of all three piezometers to the nearby stream. No groundwater was, however, recorded at this hole throughout the monitoring period. The piezometer hole at Nest 4 was the furthest away from the stream, located at the top part of the plot and since this piezometer hole was the shallowest of the three, it is not surprising that at a depth of 825 mm no groundwater was recorded.

4.2.2.1.3.2 Taylors Halt site

At the end of April 1999 the holes were established at Taylors Halt with intentions of carrying out a ground water survey. These holes were established towards the end of the monitoring period. At the time that they were established, it was observed that at a depth of 4850 mm next to Nest 2, about 18 metres away from the stream at the toe of the garden, the soil was moist but not saturated. At a depth of 4995 mm next to Nest 2, and at a distance of approximately 12 metres from the nearby stream, groundwater was encountered. This was also the case with piezometer hole established next to Nest 3, which was about 1180 mm deep and 6 m from the stream. At Nest 4 the depth of the hole was 3000 mm and the hole was 28 metres away from the stream. No groundwater was encountered at this depth. However, the soils were moist when this hole was established. Groundwater monitoring did not continue after the installation date, since the instruments were removed a few days after the installation of the piezometer access tubes.
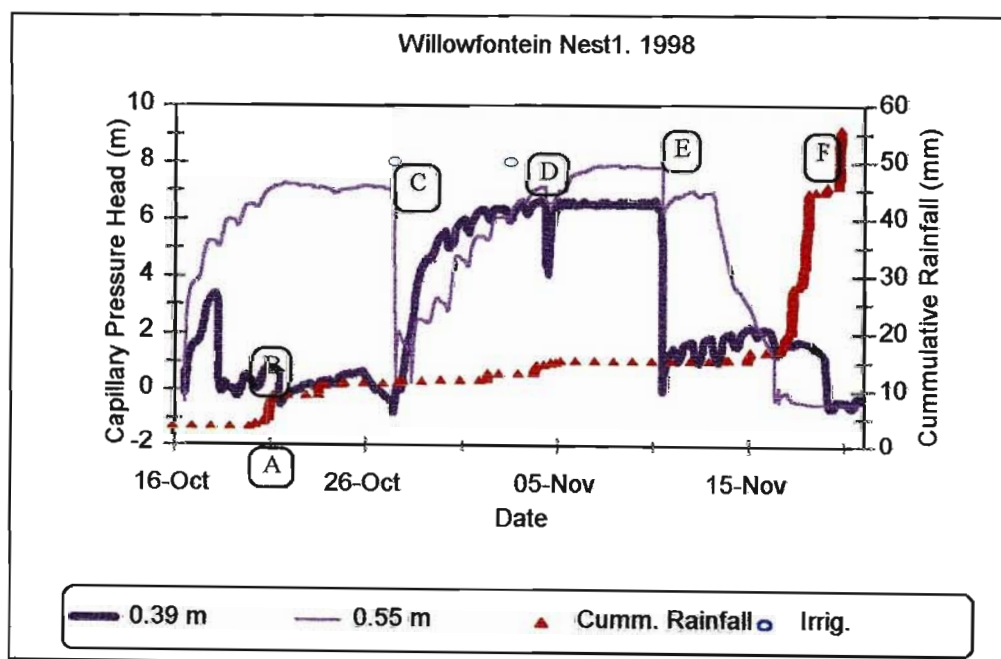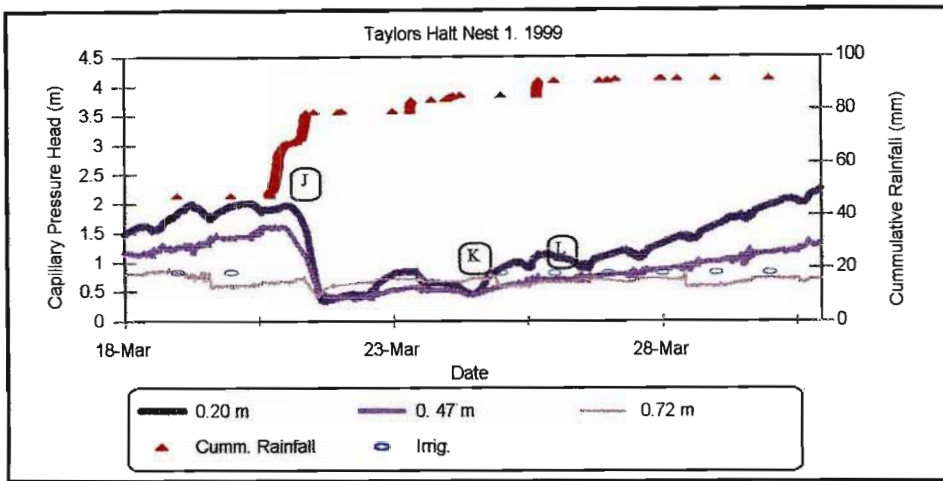
Figure 26   Nest 1, Taylors Halt tensiometer, rainfall and irrigation data
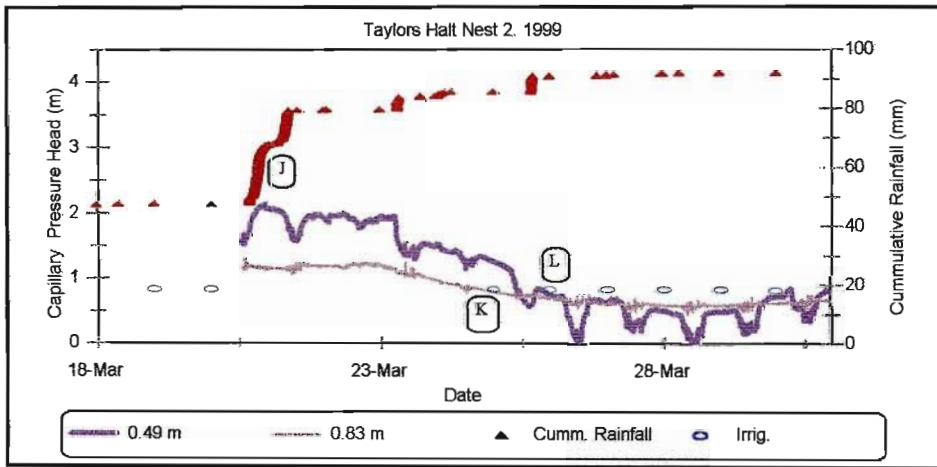
Figure 27   Nest 2, Taylors Halt tensiometer, rainfall and irrigation data
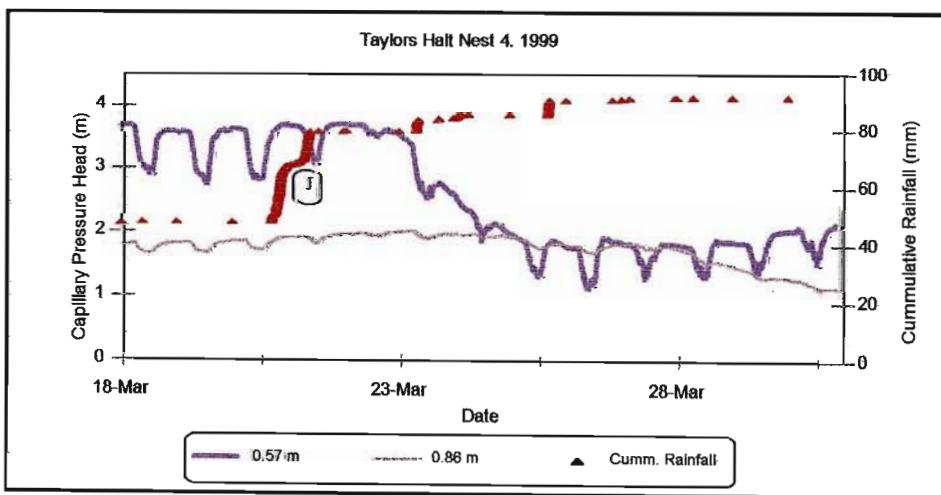
Figure 28   Nest 4, Taylors Halt tensiometer, rainfall and irrigation data

4.2.3 Modelling Results and Analysis

4.2.3.1 Willowfontein

4.2.3.1.1   Simulated Results of an Observed Scenario (SROS) vs Observed Tensiometer Data
(OTD)

Figures 29, 30 and 31 show a time series plot of simulated capillary pressure heads at the observation nodes compared to the observed tensiometer data. Careful examination of these Figures show that the observed soil water dynamics is suitably simulated by the Hydrus 2D model. The wetting of the root zone as observed from the field, particularly at 0.19 m below surface is adequately simulated by the model. The slight under simulation of CPH noticeable in Figures 30 and 31 is attributable to the bottom boundary condition which was specified as 1200 mm of constant capillary pressure head. It appears that at the lower depth water accumulation took place during the initial stage of the simulation and the water content remained constant afterwards. This water accumulation was not observed in the field, and it resulted in the under simulation of capillary pressures for the 0.72 m depth below surface. This suggests a lower flux rate out of a region, as such the constant pressure head should have been increased. However, of main importance to this study was the first 200 mm down the soil profile, where most of the root water uptake took place. In the first 200 mm, the simulated capillary pressures matches the observed well, indicating that the wetting of the root zone is adequately simulated and that the boundary conditions applied represent practice during irrigation.

Based on this, alternate irrigation strategies to optimise crop water use could be developed. Following is the discussion of the simulated efficient scenario vs the observed tensiometer data.

4.2.3.1.2   Simulated Efficient Scenario (SES) vs Observed Tensiometer Data (OTD)

Figures 32, 33 and 34 show a time series plot of the capillary pressure heads at the observation nodes for the simulated efficient scenario compared to the observed tensiometer data. In Figures 29, 30 and 31 it can be seen that all three irrigation events resulted in pronounced decrease in the capillary pressure heads indicating significant wetting beyond the root zone. Figure 32, 33 and 34 show that by increasing the number of irrigation events over the same period and reducing the amount of water applied per irrigation event, efficiencies in water application can be achieved.

This is because flux below the root zone is reduced. Since for the crops under study, the root water uptake rate was at a maximum between the CPHs of 250 mm and 3200 mm, with stress setting in at CPHs less than 100 mm and greater than 3200 mm. Reduction in unnecessary drainage could be achieved by reductions in the amount of water applied. However a certain amount of water should be allowed to drain to the other soil horizons so as to allow leaching to take place, although accumulation of salts was not reported to be a problem at the Willowfontein site. The efficient irrigation scenario presented in Figures 32, 33 and 34 constitute an increase in local knowledge, since cultivators have intuitive abilities to detect when to irrigate. For instance irrigation generally took place when the capillary pressure heads were around or close to 2 m (Figure 29). What has been shown to be an improvement would be to allow water to flow along the furrow for approximately 15 minutes instead of 30 minutes or more, but more frequently, since the soil will dry up quicker than before. That is soil moisture level at which cultivators irrigate would be reached sooner than before.

4.2.3.1.3 Analysis of the wetting plume down the soil profile

At the Willowfontein site, furrow irrigation was simulated using Hydrus 2D by specifying a hydrostatic pressure head of 0 mm over the surface nodes comprising the base of the irrigation furrow for a period of 30 minutes and 15 minutes for the observed and efficient scenarios respectively. The status of the wetting plume is shown in Figures 35, 36, 37, 38, 39, 40, 41 and 42, for both these scenarios, revealing significant wetting between the surface and 0.3 m. A wider and deeper wetted volume for the SROS (Figures 35, 36, 37 and 38) as opposed to the SES (Figures 39, 40, 41, and 42) is found. Indeed, the simulations reveal gradual dissipation of soil water after cessation of irrigation with the near surface of the SES drying up faster than in the SROS. In Figure 37 and Figure 41 the predicted wetting profile, 30 and 45 minutes, respectively, after cessation of irrigation is shown. There is a noticeable difference in the water contents of the shown cross-sections. These differences between the two scenarios can be best illuminated by the discussion below of the differences in flux at 0.63 m below surface.
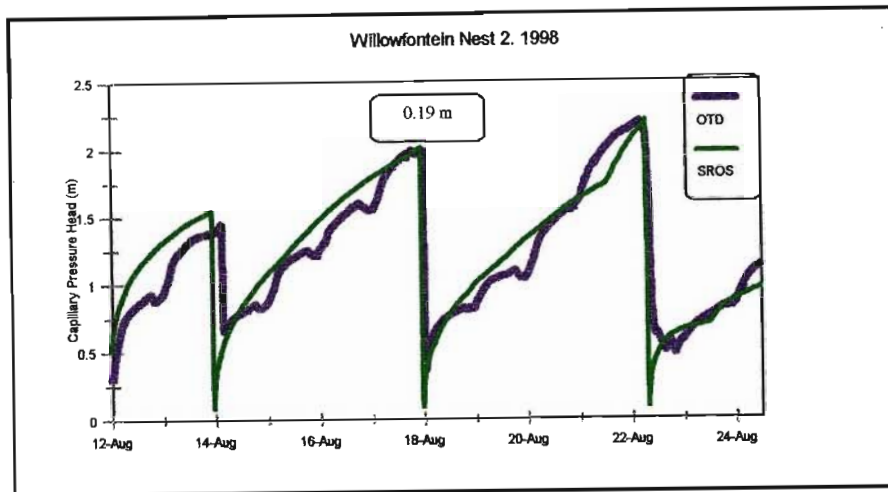
Figure 29   Simulated Results of the Observed Scenario vs Observed Tensiometer Data for Nest 2 at Willowfontein
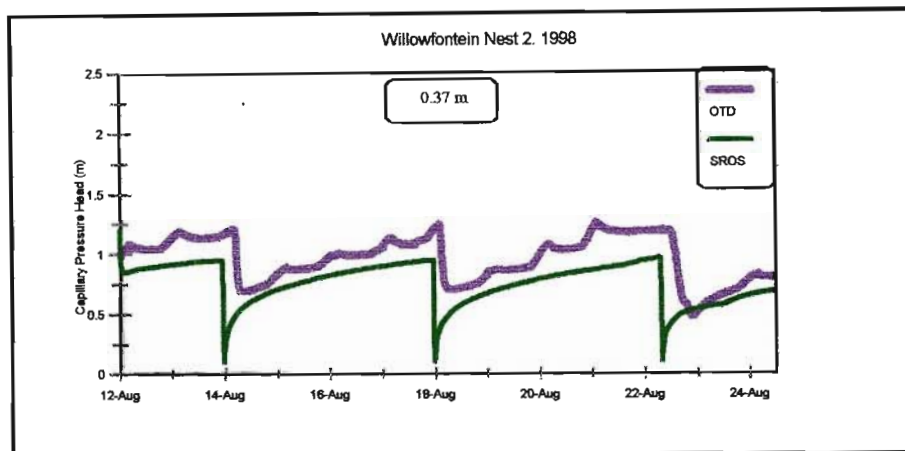
Figure 30   Simulated Results of the Observed Scenario vs Observed Tensiometer Data for Nest 2 at Willowfontein
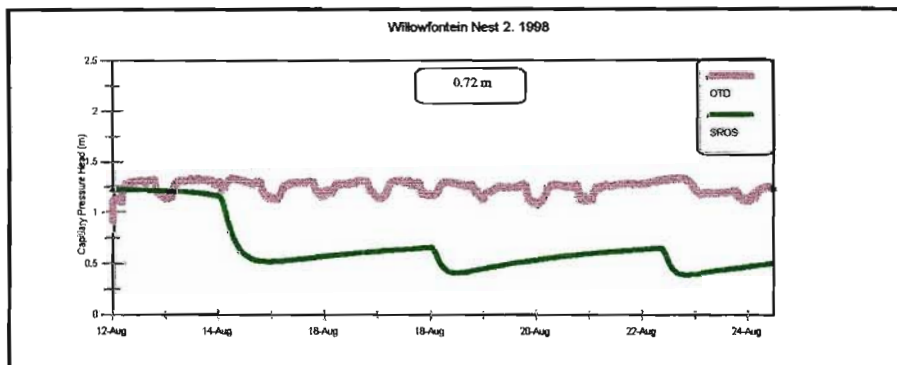
Figure 31   Simulated Results of the Observed Scenario vs Observed Tensiometer Data for Nest 2 at Willowfontein
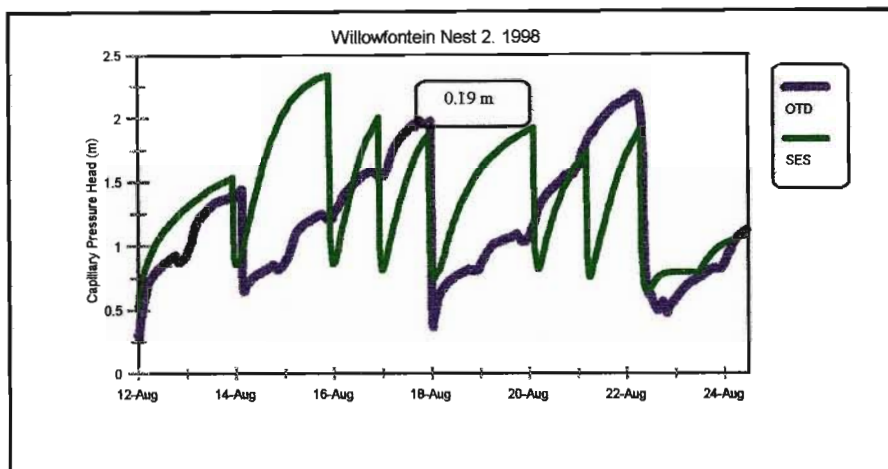
Figure 32   Simulated Efficient Scenario vs Observed Tensiometer Data for Nest 2 at Willowfontein
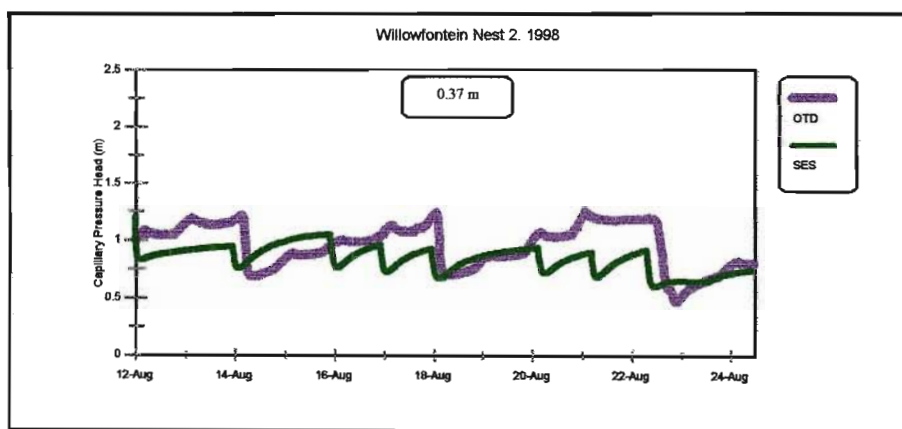
Figure 33   Simulated Efficient Scenario vs Observed Tensiometer Data for Nest 2 at Willowfontein
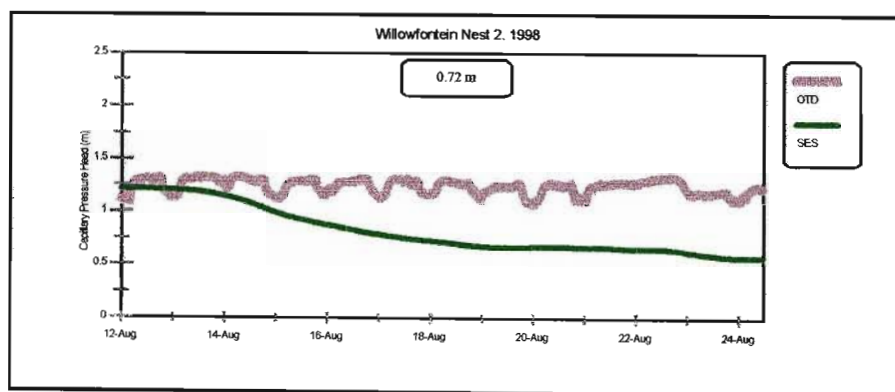
Figure 34   Simulated Efficient Scenario vs Observed Tensiometer Data for Nest 2 at Willowfontein
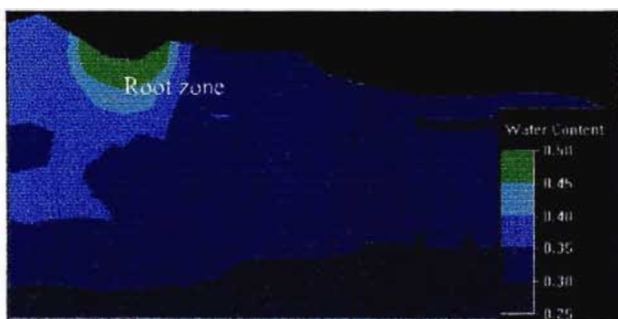
Figure 35 Water content distribution after 10 minutes of furrow irrigation for theSROS at Willowfontein

Figure 36 Water content distribution after 30 minutes of furrow irrigation i.e. At cessation of furrow irrigation for theSROS at Willowfontein

Figure 37 Water content distribution 30 minutes after cessation of furrow irrigation for the SROS at Willowfontein

Figure 38 Water content distribution after 25.5 hours from the beginning of water application for the SROS at Willowfontein

Figure 39 Water content distribution after 10 minutes of furrow irrigation for the SES at Willowfontein

Figure 40 Water content distribution 15 minutes after cessation of furrow irrigation for the SES at Willowfontein

Figure 41 Water content distribution 45 minutes after cessation of furrow irrigation for the SES at Willowfontein

Figure 42 Water content distribution after 25.5 hours from the beginning of water application for the SES at Willowfontein
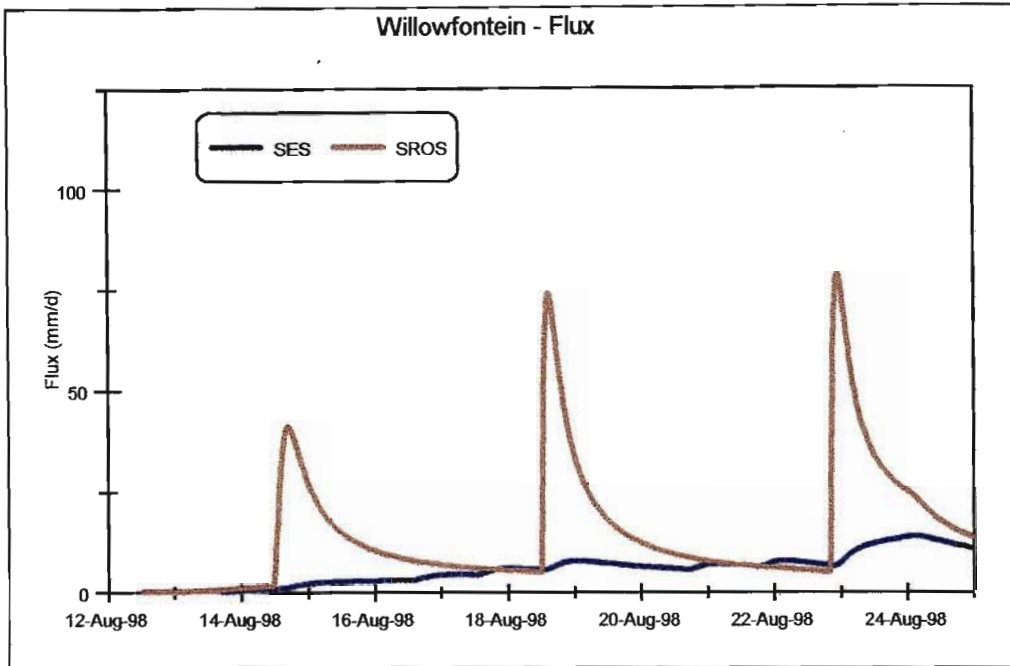
Figure 43   Soil water flux (mm.d^{-1}) at 0.63 m below surface for both scenarios at Willowfontein
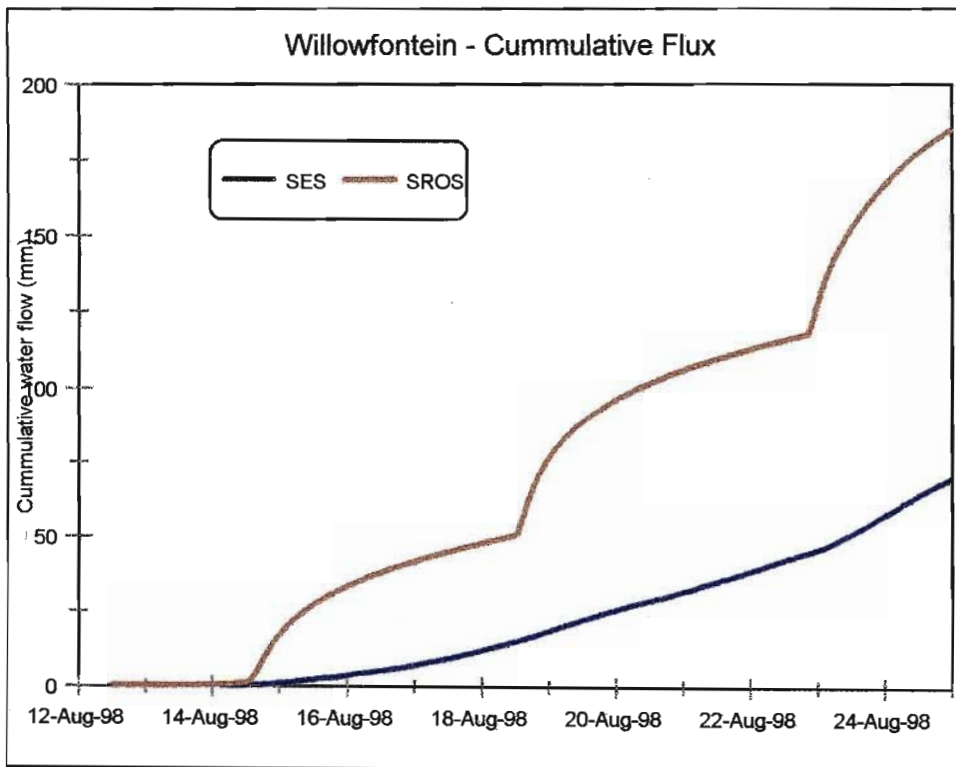
Figure 44   Cumulative water flow at 0.63 m below surface for both scenarios at Willowfontein

4.2.3.1.4 Differences in flux as modelled at 0.63 m below surface

For the selected period the quantity of water applied was, without exception, consistently higher for the SROS as opposed to the SES (with its restricted application amount). The quantity increased as more time was allowed to elapse between irrigation events. This is evidenced by the daily fluxes corresponding to irrigation events (Figure 43). Cumulative fluxes show pronounced changes in flux corresponding to irrigation events, even at a depth of 0.63 m below surface (Figure 44). However, these pronounced changes are not noticeable in the cumulative flux of the SES, and a change to a more water efficient irrigation practice would result in the water saving of approximately 115 mm for the selected period (Figure 44) as there is less drainage below 0.63 m with the SES.

4.2.3.2 Taylors Halt

4.2.3.2.1 Simulated Results of an Observed Scenario (SROS) vs Observed Tensiometer Data (OTD)

A time series of Taylors Halt tensiometer data plotted against the simulated capillary pressure head at the observation nodes is shown in Figures 45, 46 and 47 for depths 0.2, 0.47 and 0.72 m below surface. These simulations show that, within reasonable limits, the Hydrus-2D model has simulated the capillary pressure heads at the three observation points below the soil surface adequately, especially as the whole profile is simulated in Hydrus-2D. This adequate fit of all three depths comprises a fairly good simulation. However, anomalies are noticed on March 12th and 15th at 0.47 m below the soil surface, where the tensiometer did not reflect any associated decrease in the capillary pressure head following a rainfall event. There does not appear to be a logical explanation for this observed anomaly, since subsequent rainfall events of smaller quantities caused a substantial drop in the capillary pressure head. Reasoning suggests that some sort of water diversion away from the ceramic tip took place for these two events or that the soil was too dry to respond to the first two events but responded to the later events. Data from the field monitoring of irrigation events does not show any pronounced associated decreases in the capillary pressure head as a result of the 18 mm of water applied locally to the crop every irrigation event. What can be said about this water application is that in addition to making some water available for the plants, it significantly reduced the drying rate of the soils.

As with Willowfontein, of main interest to this study was the 200 mm below the soil surface, where most of the root water uptake took place. In the upper 200 mm the simulated capillary pressure heads closely match the observed, indicating that the wetting and drying of the root zone is adequately simulated and that the boundary conditions applied represent the practice during irrigation.

Based on this ability to simulate observed conditions acceptably (Figures 45, 46 and 47), alternate irrigation strategies to optimise crop water use could be developed. Below is a discussion of a typical Simulated Efficient Scenario (SES) vs Observed Tensiometer Data (OTD).

4.2.3.2.2   Simulated Efficient Scenario (SES) vs Observed Tensiometer Data (OTD)

Figures 48, 49 and 50 show simulated capillary pressures at the observation nodes of the simulated efficient scenario plotted against the observed tensiometer data. It is clear that optimum crop water use could be achieved by reducing the number of irrigation events and allowing capillary pressures to increase, but without exceeding the limits at which crops become stressed. Crops investigated at Taylors Halt were similar to those at Willowfontein, with maximum root water uptake taking place at capillary pressure heads between 250 mm and 3200 mm and stress setting in at capillary pressures less than 100 mm and greater than 3200 mm (Figure 15). It can be seen from observed data that for the selected period capillary pressure heads were generally maintained within these thresholds (Figures 45, 46 and 47). While the proposed efficient scenario (Figures 48, 49 and 50), allow capillary pressures to increase as a result of the decrease in frequency of irrigation events, cognisance of the need to allow some water to drain to the underlying soil horizons was given due attention, since this is essential for the leaching of salts to take place. This consideration was made despite the fact that the problem of salts has not been reported to have reached alarming proportions in Taylors Halt. Unlike at Willowfontein, where intuitive ability of the growers to detect when to irrigate from observations of the soil dryness seems to be just about right, at Taylors Halt, the frequency with which cultivators irrigate their crops seem to be purely to satisfy ground rules laid down for all the cultivators within the group. One of the rules in the Taylors Halt group is that failure to irrigate crops regularly could lead to expulsion of that particular member from the group. Thus the soil moisture status is not given sufficient prior attention before proceeding with subsequent irrigation events. Against this

background, cultivators would need technical support if they are to change over from their current practices to the proposed efficient scenario. This support would be to enhance their understanding of the soil moisture status at which they need or do not need to irrigate their crops.

Before proceeding to the observed differences in flux between the two irrigation practices (i.e. the Simulated Results of the Observed Scenario (SROS) and the simulated efficient scenario (SES)), the section below analyses the soil moisture status at the root zone.

4.2.3.2.3   Analysis of the soil moisture status of the root zone at Taylors Halt

At Taylors Halt, bucket type or hand irrigation was simulated by specifying equivalent amounts of rainfall input on the recorded irrigation dates. The soil moisture status is carefully analysed for the two scenarios (Figures 51, 52, 53, 54, 55 and 56). For the selected period, following the last major rainfall, for the SROS, Figures 51, 52 and 53 show the water content to have been higher in the root zone compared to the SES (Figures 54, 55, 56). This difference in water content is attributable to the frequency of water application despite sufficiently wet conditions for the crops. The water content on 23 March 1999 is uniformly higher (Figure 51) than for the same date in the SES (Figure 54), when the water content in the root zone was in the 0.45 - 0.50 range, which was less than the surrounding soil. This is largely because after cessation of rainfall event irrigation took place in the case of the SROS (Figure 51), whereas no irrigation took place in the SES (Figure 54).

Two days after the major rainfall event had ceased, drying of the root zone is noticeable in both scenarios on the 24th March 1999 at 12:07 PM. The difference is that the extent of drying up is larger for the SES (Figure 55) than it is for the SORS (Figure 52). This drying is noticeable since no supplementary irrigation took place in the period between 23rd March 1999 at 12:07 PM and 24th March 1999 at 12:07 PM.

On the 26th March 1999 at 12:07 PM there are still noticeable differences between the SROS and the SES (Figures 53 and 56), despite the rainfall contribution and supplementary irrigation which took place on the 25th March 1999. These differences are attributable to the antecedent moisture conditions prior to rainfall and irrigation. This analysis indicates quicker drying response of the root zone with the SES as opposed to the SROS. This is as a result of the reduction of excess

water in the root zone with the proposed SES.

In general these differences in water contents are indicative of the efficiencies in water application that are likely to be achieved by changing over from current practices at Taylors Halt to proposed efficient irrigation practices. This mainly involves reduction in the frequency of hand irrigation following rainfall events and when soil moisture conditions within the soil profile, particularly within the root zone, are within acceptable limits. The discussion of the differences in flux further illuminates the savings in water that could be achieved through the more efficient irrigation application proposed.

4.2.3.2.4 Differences in flux as observed at 0.5 m below the soil surface.

For the selected period, downward water flux of the SROS was consistently higher than water flow of the SES (Figure 57). An increase in daily flux is observed following a major rainfall event which occurred on the 22 March 1999. A steady decrease in fluxes follows after cessation of this rainfall event. This steady decrease in fluxes can be explained to be as a result of frequent irrigation by the cultivators at Taylors Halt, who do not give much attention to antecedent soil soil water content conditions. Comparison of the fluxes of the two scenarios (Figure 57) shows that the daily fluxes of the SROS are higher than that of the SES. This indicates that more water is lost by downward percolation in the case of the SROS as opposed to the SES. Cumulative flux (Figure 58) shows that a change over from current irrigation practices to the proposed efficient scenario would contribute to a reduction of 79.6 mm of water lost by downward percolation below a depth of 0.5 m for the selected period.
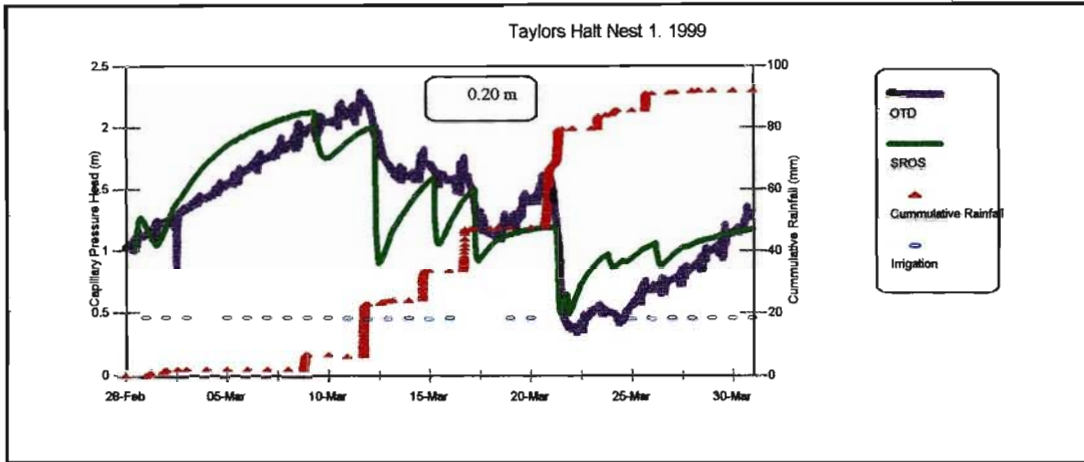
Figure 45   Simulated Results of the Observed Scenario vs Observed Tensiometer Data for Nest 1 at Taylors Halt
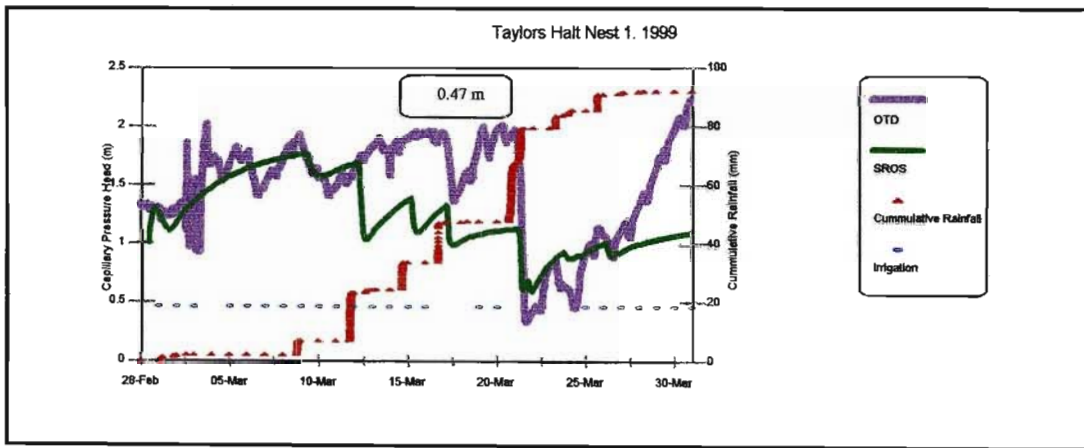
Figure 46   Simulated Results of the Observed Scenario vs Observed Tensiometer Data for Nest 1 at Taylors Halt
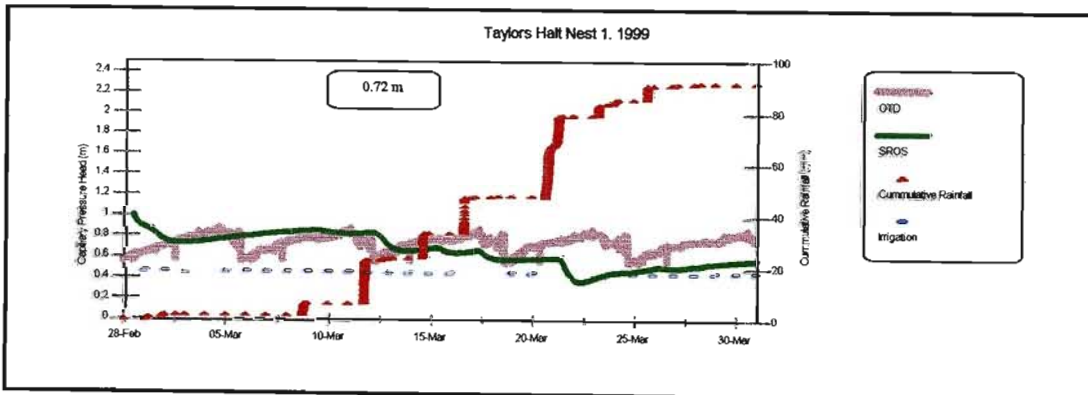
Figure 47   Simulated Results of the Observed Scenario vs Observed Tensiometer Data for Nest 1 at Taylors Halt
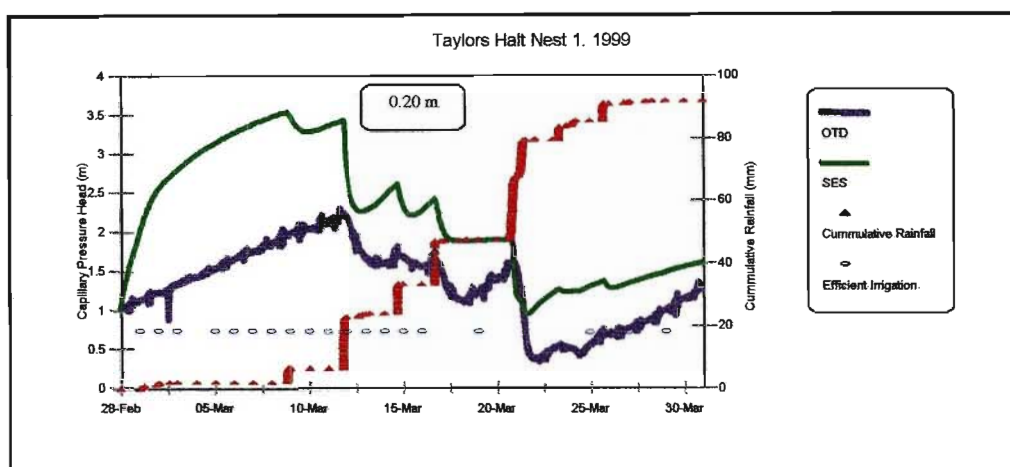
Figure 48   Simulated Efficient Scenario vs Observed Tensiometer Data for Nest 1 at Taylors Halt
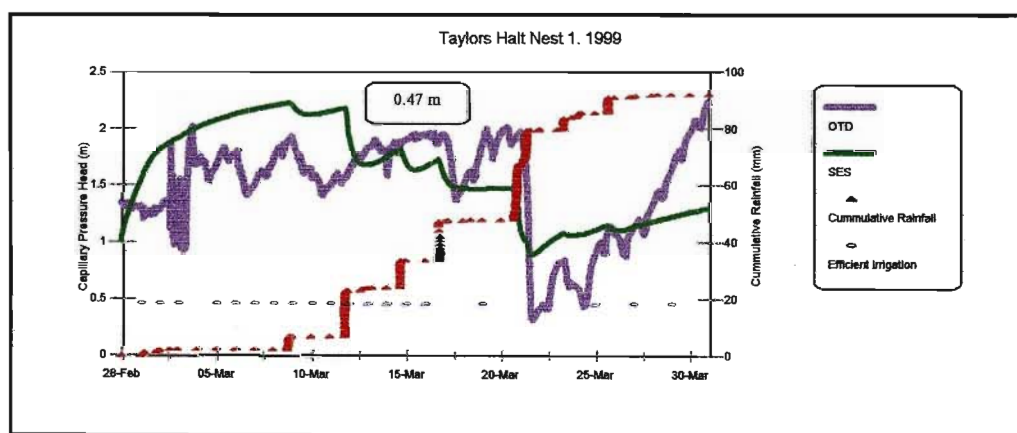
Figure 49   Simulated Efficient Scenario vs Observed Tensiometer Data for Nest 1 at Taylors Halt
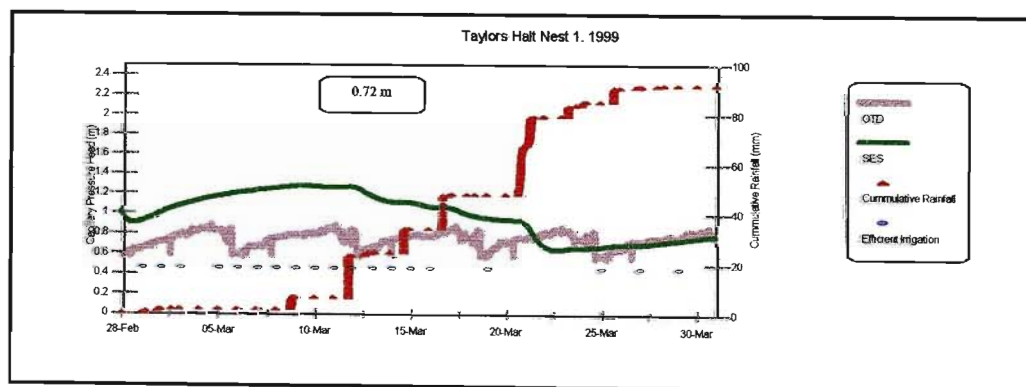
Figure 50   Simulated Efficient Scenario vs Observed Tensiometer Data for Nest 1 at Taylors Halt
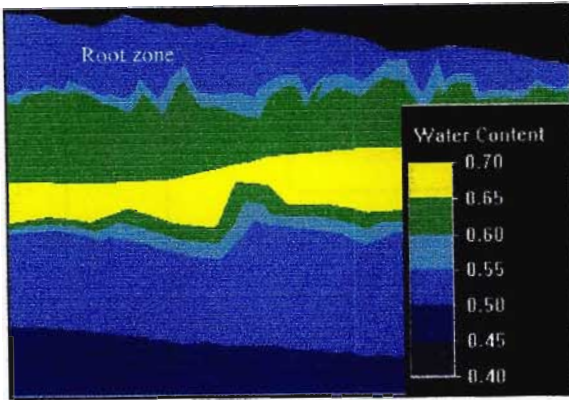
Figure 51 Water content distribution on the 23rd March 1999 at 12H07
PM for the SROS at Taylors Halt
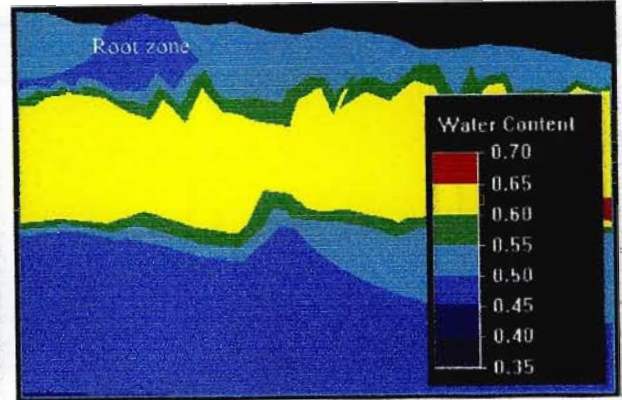
Figure 54 Water content distribution on the 23rd March 1999 at 12H07
PM for the SES at Taylors Halt
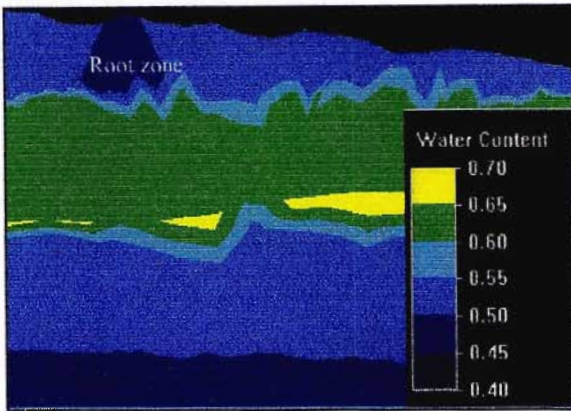
Figure 52 Water content distribution on the 24th March 1999 at 12H07
PM for the SROS at Taylors Halt
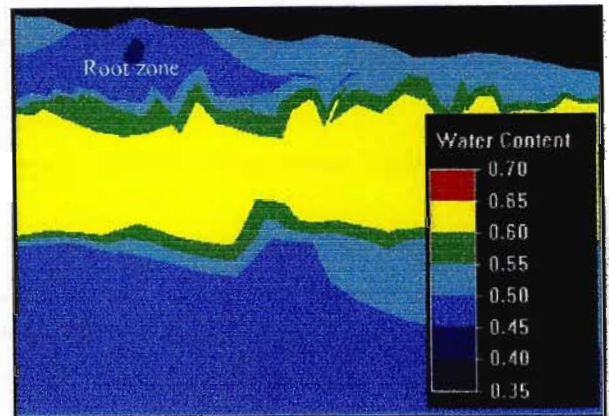
Figure 55 Water content distribution on the 24th March 1999 at 12H07
PM for the SES at Taylors Halt
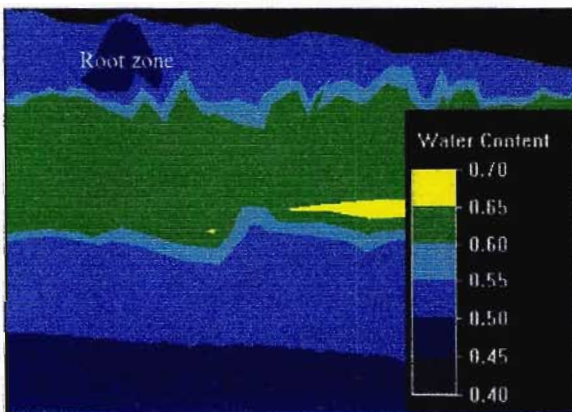
Figure 53 Water content distribution on the 26th March 1999 at 12H07
PM for the SROS at Taylors Halt
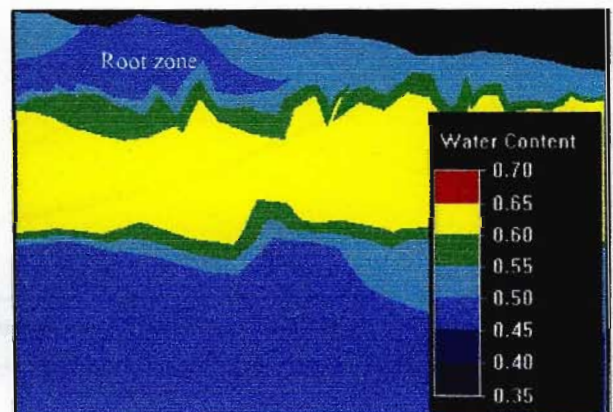
Figure 56 Water content distribution on the 26th March 1999 at 12H07
PM for the SES at Taylors Halt
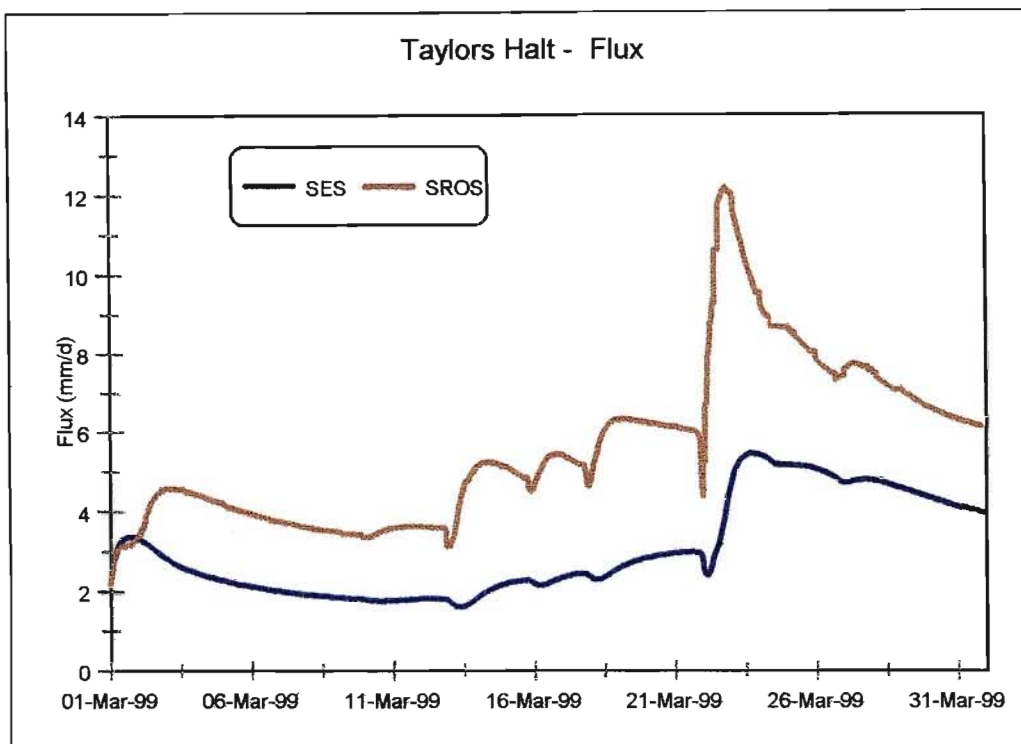
Figure 57 Water flux (mm.d⁻¹) at 0.5 m below surface for both scenarios at Taylors Halt
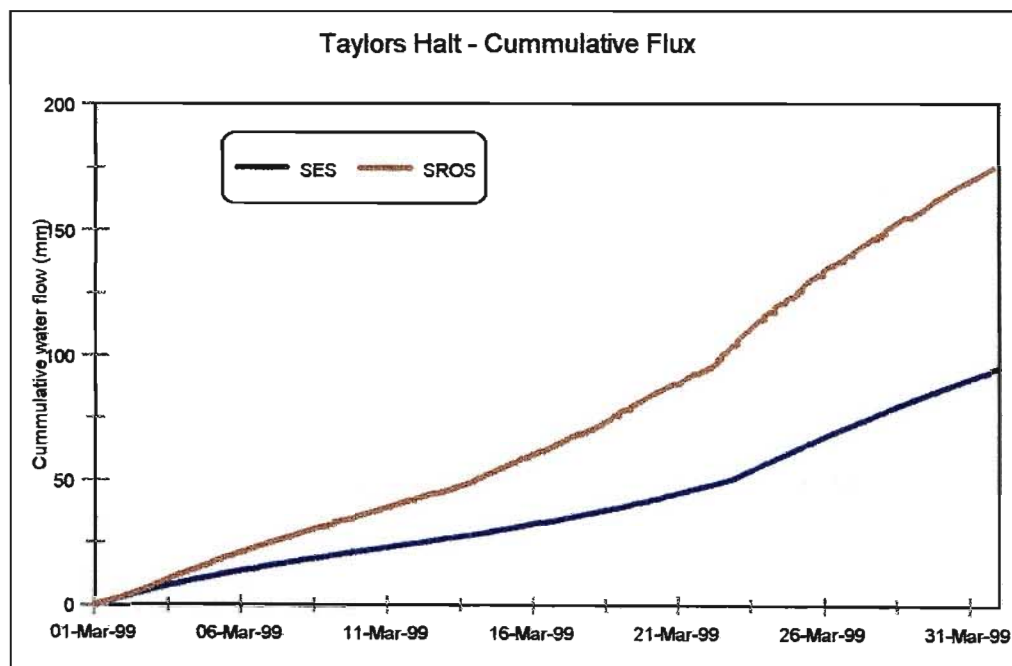
Figure 58 Cumulative downward flow at 0.5 m below surface for both scenarios at Taylors Halt

5. GENERAL DISCUSSION

In South Africa, like the rest of Sub-Saharan Africa, the establishment of small scale irrigated vegetable plots is increasing. Collier and Field (1988) have observed that "Small irrigated vegetable plots, grouped into communal village gardens and supplied with water from a hand pumped well are of increasing interest to Sub-Saharan Africa, especially to women". This increase in small scale community vegetable plot activity is largely due to the socio-economic pressures exerted by the poor economic performance of many African States. Therefore, small scale community vegetable gardening is seen by the vast majority of the unemployed to be critical to reduction of poverty. There is certainly sufficient observable evidence of this increase in gardening activity in South Africa (Crosby, de Lange, Stimie and van der Stoep, 2000). Urban and peri-urban communities, which over the years disregarded growing their own vegetables, are now heavily involved in community gardening, an activity often referred to as urban agriculture.

With this increase in community gardening huge pressures have been exerted on government and other funding NGO sectors to provide financial resources necessary to establish community gardens with proper irrigation infrastructure. In response to these pressures, the government through the Department of Agriculture provides deserving community groups with funds to establish a community garden with proper irrigation infrastructure. Various NGO's and some other private sector companies, in particular the United Nations Life Programme, have supported the establishment of some community gardens in the Pietermaritzburg area of South Africa. Whilst these organisations need to be applauded for their contribution towards the alleviation of poverty in South Africa, caution should be exercised in order to avoid repeating the mistakes of the past government (e.g. provision of sophisticated irrigation infrastructure in the absence of maintenance and support systems). There is also a need for all stakeholders to partake in the process of finding solutions to many of the problems facing small scale agricultural development in South Africa. Ignoring these problems might undermine the good intentions of government, NGO's and other private sector organisations.

Failure of many small scale irrigation projects that were supported by the previous government was largely attributed to the top down approach which disregarded participation by the target

beneficiaries during planning and subsequent stages of the project. This happened despite the demonstration by local research of the need for a change in the planning and development of irrigation schemes in South Africa (Bembrigde, 1997). It is imperative that the present government adopt an integrated and holistic approach in its endeavours to assist small scale agricultural development. When doing so, the government would not be seen to be providing financial assistance from some remote location, but would provide this assistance in the context of policies, legislation, provincial and national objectives that are informed by an inclusive interactive process among stakeholders. This appeared to be a highly desirable approach by the growers interviewed in this study, since the government is perceived to be an integral player to finding solutions to many of the constraints facing small scale agricultural development in South Africa.

South Africa has a long way to go in removing the damage that has been inflicted as a result of development policies and programmes which did not recognise the need for consultation and community participation (van Averbeke, Belete, Igodan and Marete, 1988). Evidence of this is the mis-match between the organisational basis surrounding water use and allocation and the irrigation infra-structural developments supported by the previous government. De Lange (1994), in her study of small scale irrigation systems in South Africa, listed the following as some of the additional problems exacerbating the complexity of small scale irrigation development in South Africa:

▸ Lack of water supply for irrigation purposes,

▸ Lack of assured water supply

▸ Shortage of water supply technology,

▸ Lack of technical support,

▸ Lack of guidance, and

▸ Ineffective and inefficient management styles.

De Lange (1994) also revealed the need to investigate actual crop water use to enable recommendations to be made to small scale irrigators, since the results of her field evaluations combined with information from the farmers, suggested that less irrigation water was applied than is generally recommended for maximum crop yields.

In order to understand the current state of small scale irrigation in South Africa and elsewhere, so as to identify common problems and approaches used to solve those problems, an extensive literature review was undertaken (Chapter 2). It is worth mentioning that literature reviewed revealed that little research has been done in South Africa in terms of investigating actual crop water use and soil water dynamics in small scale agricultural conditions. Therefore, this work was possibly the first of its kind to investigate the combination of socio-economic issues pertinent to small scale irrigation development and technical issues pertinent to the crop soil-water continuum in order to develop a methodology for assessing small scale community gardening irrigation holistically. In particular, the technical aspect of this research was consistent with the particular research needs identified by de Lange, 1994.

The review of literature indicated that participation in small scale agriculture is predominantly by women. This was found to be true, since both the Willowfontein and the Taylors Halt group were predominantly women. This study has highlighted many constraints which continue to hinder progress with regards to small scale agricultural development. Many of these problems, as identified by other researchers elsewhere, were found to prevail at Willowfontein and Taylors Halt. The lack of management skills, technical support, shortages of capital, irrigation infrastructure, assured irrigation water supply, lack of supply technology and inadequate extension services are all problems that have been identified by other researchers. These problems were all evident at the both sites of this study. The two groups realise that these problems pose serious constraints to their development, and it is for that reason that they would like to receive training to overcome some of these problems.

In addition to these problems, perceptions that the cultivators hold about their gardening projects are further constraints to their development. There is a strong donor dependency among participants in small scale community gardening. This was established during the course of interviews conducted during this study. This dependency emanates from the perception that community gardeners are entitled to funding from the government or any other funding agents, for the initial establishment and /or purchasing of agricultural inputs. Since these projects are never fully funded in terms of their needs, they continue to seek additional funds in many instances without success. In the hope of securing additional funds they lose their innovative urge and creativity to make the project self sufficient, and hence many of these projects never progress to

become fully fledged business enterprises. Although they are mainly established with twin aims of providing food security and of augmenting family income, there seems to be growing realisation from participants that for self sufficiency to be achieved and for continued realisation of their aims, these projects need to be managed in a proper business manner. Although not impossible, this remains a serious challenge for community gardeners given their communal arrangement.

In winter, water shortages at Willowfontein were not as serious as they were at Taylors Halt. Virtually no gardening activity took place during the winter season at Taylors Halt. This was because of inadequate water supply. To improve the irrigation infrastructure at both sites, cultivators aspire to install sprinkler irrigation systems should funds become available. It was also evident in this study that when cultivators experience problems of inequity in water allocation during irrigation, they tailored rules to ensure equity of water allocation during irrigation (e.g. the rotational system which applies at Willowfontein). Since these projects were managed by the cultivators themselves, rules governing operations were made with close reference to the problem, and as such they were relatively effective. Studies elsewhere have shown that rules crafted and implemented by external agencies removed from the problem proved to be ineffective and to a large extent destabilised operations (Lam, 1996). This was found to be true, since at Willowfontein it was the development committee for the area that decided who could be expelled from the gardening group and not the gardening group management committee. A consequence of this was that some plots were left fallow for the entire season as the project management committee could not intervene. At Taylors Halt, rule crafting was done by the cultivators themselves with no external interference. The operations of the group were uniform and the entire plot looked uniform throughout the summer season. None of the sub-plots were left fallow during the summer season during which this study was conducted.

While cultivators on both research sites may have reasonable reasons underlying their aspirations to install sprinkler irrigation systems, a number of researchers on small scale irrigation systems suggest that a thorough investigation be conducted on appropriate technology suitable for use under developing conditions, prior to any decision being taken on which system to use(Crosby, *et al*, 2000). They add that the design and installation of these systems should consider the socio-

economic factors prevailing under those conditions and this would include rules and existing systems of water allocation and distribution. Success stories have shown that taking these factors into consideration during system design and installation prevents failures similar to that of the Village Irrigation Rehabilitation Programme (VIRP) in Sri-Lanka (Abeyratne, 1990). In addition, appropriate technology must be within the cultivators financial and operating capabilities.

Since irrigated community gardening is increasingly becoming a common land use, it is likely to have a significant impact on water resources. It is therefore essential to assess current irrigation practices and to make recommendations on efficient irrigation practices where necessary. This way, benefits can be optimised from the use of limited water resources. This assessment requires an understanding of the crop soil-water continuum, hence, the technical aspect of this study.

Given that the technical aspect of this study required an understanding of the crop-soil water dynamics and the modelling of processes observed, it was necessary to obtain the soil hydraulic properties representative of field conditions. This objective was achieved through determining the saturated and unsaturated conductivities, and the water retention characteristic curves at the surface and at various depths down the soil profile for both sites. The tension infiltrometer and the double ring infiltrometer methods were used (Chapter 3). These methods were used because infiltration rates effectively integrate properties of the porous media, including the influence of local scale heterogeneity, different soil structure and texture irregularities, preferential pathways, layering and anisotropy. The laboratory controlled outflow cell method was used to determine the water retention characteristic curves at different depth down the soil profile, and bulk densities were obtained from this method for the corresponding depths. Although laboratory analysis of the soil textural properties was not carried out in this study, hydraulic conductivity results show differences in surface conductivities between the four nests at Willowfontein. These differences in conductivity are reflective of looser soil structure on some patches of the cultivated area, indicating inconsistent and uneven land preparation at Willowfontein. Observation made during the process of conducting on site experimentation at Willowfontein were that the surface soil structural and textural properties appeared to be similar for all four nests, with the clay content increasing with increasing depth below the soil surface. Hydraulic conductivity results show a decrease in conductivity with increasing depth below the soil surface. This is possibly because of increased compactness down the soil profile. The water retention characteristic curves down

the soil profile at Willowfontein show a decrease in water content at field capacity (Appendix E, Figures E2, E4 and E6). This means that less water compared to the top soil horizon will be held by the mid-profile at field capacity before drainage to the next soil horizon occurs. Bulk densities also increased for the various depths below the surface, this is likely to be caused by an increase in the compactness of the soil down the soil profile.

Since at Taylors Halt land preparation was fairly consistent throughout the field, unsaturated conductivities at the four nests were close, with conductivities at Nest 1 higher than the other nests, which was attributed to looser soil structure in the vicinity of Nest 1. Both saturated and unsaturated conductivities at Taylors Halt decrease with increase in depth below surface. The water retention curves (Appendix E, figures E8, E10 and E12) show a higher water content for the mid-profile compared to the top and lowest profiles. This shows that the mid-profile will hold more water at field capacity than the other two profiles before any drainage to the soil horizon below occurs. The increase in bulk density down the soil profile, with increase in depth below the soil surface is likely to be due to increased compactness of the soil down the soil profile.

Comparison of the hydraulic properties of the two sites show that, generally the hydraulic conductivities at Taylors Halt are higher than the hydraulic conductivities at Willowfontein.

One of the objectives of this study was to determine the influence of rainfall on irrigation patterns at both the sites, as well as water application efficiency during irrigation. Tensiometry was used for these purposes. Automated tensiometers were selected for use in this study because in addition to having a successful track record for continuous measurement of soil water tension in the field, tensiometers allowed measurement of the energy status of the soil water at three different depths below the soil surface. From the measurement of the energy status of soil water, one can determine the hydraulic gradient, direction of flow and water content. In this regard, tensiometry appeared to be the best option for use in this study, given that it is also relatively cheap to construct and maintain compared to other techniques. This was an important factor to consider in selecting a monitoring technique for use in the described conditions. With limited funding, one had to choose low cost instruments which were robust and that allowed direct measurement of the energy status of soil water.

Analysis of tensiometer, rainfall and irrigation results are presented in section 4.2.2.1.1 and 4.2.2.1.2 for Willowfontein and Taylors Halt respectively. From these results it is clear that at Willowfontein each cultivator determines his/her irrigation schedule at a sub-plot level. Irrigation scheduling is not decided upon at a plot or field level, and hence application is not uniform for all the cultivators. It is dependent largely on the intervals between irrigation events, the quality of the crops grown on the sub-plot and the amount of time the cultivator has to irrigate. The results also show that cultivators apply more water than necessary during irrigation events to compensate for the large intervals during which no irrigation takes place. Excess water, in turn, drains to the soil horizons beyond the densely populated root zone and is therefore wasted. During the wet summer season (December) no supplementary irrigation was recorded at Willowfontein. This was equally true for all the monitored summer months, indicating heavy reliance on rainfall input despite sufficient water for supplementary irrigation.

At Taylors Halt one of the rules governing operations is that no crops should show signs of stress. As a result cultivators irrigate almost on a daily basis provided that water is available. Unlike at Willowfontein, irrigation at Taylors Halt is mainly supplementary irrigation since the gardening activity only take place during the wet summer season. Analysis of results as presented in section 4.2.2.1.2 show that water applied during irrigation events at Taylors Halt was not sufficient to cover the entire root zone. It was enough, however, to reduce the drying of the surface and near surface soil, thus causing the soil to be kept relatively wet and even wetter than it would be if water was applied via an efficient strategy.

From the analysis of rainfall, tensiometer and irrigation data, it is quite evident that irrigation patterns are dependent on the enforcement of rules. Where there were strict rules governing irrigation of crops, uniformity of water application throughout the plot was observed, and where the rules were not strictly enforced, cultivators determined their own patterns of irrigation. It can also be mentioned that when water shortages are experienced, it is then that cultivators devise irrigation systems that seek to prevent conflict among themselves e.g. the rotational system in use at Willowfontein.

In Chapter 4, the modelling results of both the sites are presented. It was shown that the HYDRUS-2D model simulated the observed data well, especially at 0.19 m below surface at Willowfontein where most of the roots were found. However, improvements on the model performance in simulating matric pressures at the other two depths below surface at Willowfontein could be achieved by increasing the constant pressure head of the bottom boundary condition. Modelling results show that at Willowfontein, irrigation efficiencies could be achieved by reducing the amount of water applied per irrigation event and increasing the frequency of irrigation events. At Taylors Halt, by reducing the number of irrigation events following a rainfall event which sufficiently wetted the root zone, efficiencies could be achieved from a water application view point. At both Willowfontein and Taylors Halt, the proposed alternate strategies would still allow sufficient water to drain to the underlying soil horizons for leaching purposes. In the modelling exercise undertaken over a period of a month, these efficient strategies resulted in significant water saving of 115 mm and 79.6 mm of water, at Willowfontein and Taylors Halt, respectively. Contrary to the results of the evaluation conducted by de Lange (1994), which suggested that less water was applied in small scale irrigation systems than is required for maximum crop yields, these results show that more water was applied in both sites than required for maximum crop yields. It is for this reason that the HYDRUS-2D modelling system has been used to develop and evaluate efficient irrigation strategies.

Based on the work discussed on the preceding sections, a methodology for assessing small scale community gardening irrigation has been developed and is discussed in the following section.

5.1   Methodology for assessing small scale community gardening irrigation

In the evaluation of a community irrigation project the following actions should be taken:

▸   Highlight the following benefits that would accrue to the local community as a result of such an assessment being carried out succesfully:

–   information on appropriate irrigation strategy (quantity and timing),

–   more water made available for other uses following efficient irrigation practices,

–   assessment would aid the design of appropriate infrastructure that is consistent with existing systems of water allocation and distribution and

–   would enhance their understanding of the crop water requirements.

▸   Establish the institutional and organisational basis surrounding water allocation and distribution in the area.

▸   Establish existing patterns and rules governing in-field irrigation and the reasons behind such patterns and rules.

▸   Establish the hydraulic properties of the soils at the surface and different depths below surface.

▸   Measure and monitor the rainfall contribution and note its influence on irrigation patterns and water application efficiencies.

▸   Measure and monitor the quantities of water applied per irrigation event, the interval between irrigation events, and the depth of the wetting front following an irrigation event. Simple monitoring devices such as the wetting front detector could be a useful substitute for the intricate tensiometer used in this research project.

▸   Select a modelling system suitable for use at the required scale and with available data and measured data.

▸   Develop alternate irrigation strategies if necessary, these strategies should be consistent with existing rules and local objectives of water use.

▸   Advise the local community or the gardening group together with all stakeholders of the results of the assessment and advise them on the appropriate irrigation technology.

In the course of carrying out this study a few problems were experienced, these problems were relatively insignificant given that work of this nature had not been carried out in the described

conditions before. However, it is important to highlight them so that other researchers intending to pursue studies in conditions similar to the ones described in this study can be made aware of them. Some of these problems were not directly experienced by the researcher but were experienced by other social sciences researchers, whose research was being conducted at the same time as this one at Willowfontein. These problems are pointed out in the section below.

5.2   Problems and pitfalls in assessing community gardening irrigation

Consultation is critical to the success of an assessment of this nature. The consultation process should involve all stakeholders at the very outset of the project. In the past, researchers who failed to thoroughly consult with all stakeholders prior to conducting research in the described conditions have been met with resentment. This resentment manifests itself in the destruction of instrumentation where the projects involves technical measurements and monitoring, and/ or unwillingness to participate in interviews or fill in questionnaires. Communities residing in conditions similar to Willowfontein and Taylors Halt, view the lack of consultation as a sign of disrespect and disregard for their potential contribution to the research being done. Therefore, researchers who intervene without proper consultation are perceived as people claiming to be more knowledgeable than locals, and coming to offer solutions which would alter existing systems and patterns of social behavior. They are seen as completely disregarding local knowledge, since it was judged inferior to their own. These perceptions and fears need to be allayed from the very outset so as to tap in on existing local knowledge and to gain maximum co-operation from the local communities.

Customary practices also need to be given thought as they might affect the schedule of tasks and data collection. During the course of carrying out the study at Taylors Halt, a local chief died and because of this no one was allowed to do any agricultural work in the area for three months following the death of the chief. This was normal practice in the area and was done to mourn the death of a high profile person. Researchers had to obtain special permission to be able to continue with data collection. During the consultation stage of the project researchers need to explain to all stakeholders that data collection is a process that might drag on for months. Therefore, to achieve good results and for positive benefits to accrue to the local community at the end, the

process of data collection needs to be exempt from customary practices.

Since data collection cannot always be automated, especially under developing agriculture conditions, it is important to ensure that data which needs to be collected by the local people are recorded correctly and that the individuals chosen for the task are capable of carrying this out. In this regard problems were experienced at Willowfontein with recording irrigation dates. This was the case because some cultivators who were required to record dates whenever they irrigated their sub-plots could not read and write. Hence they asked their children of school going age to record the dates for them. These children would record incorrect dates which did not correspond with tensiometer data as they were never in the community garden during irrigation. A simple wetting front detector developed by SCIRO/UP is a simple method that could be used to eliminate this problem.

Contrary to the expectations of skeptics, not a single monitoring instrument was deliberately destroyed by the local community members during the course of carrying out this study. This was attributed to the co-operation that researchers enjoyed from the group members and general community members. From this experience it could be suggested that proper and thorough consultation minimises chances of destruction to instrumentation, owing to the fact that consultation provides local community members with an opportunity to understand the intentions of research and how the research would benefit them at the end, therefore, it is essential to maintain good communication and interaction between researchers and local community members throughout the research. The other contributing factor to this success was that the postgraduate researcher could speak the local language fluently as it was his first language, so communication was effective. This is an important point to consider when conducting research in conditions similar to Willowfontein and Taylors Halt.

Local community members expressed unequivocally to the postgraduate researcher that they were not co-operating with some researchers who came to the area with questionnaires and requested them to fill in these questionnaires. They pointed out to the post graduate researcher that they were tired of answering questions from people who came out of nowhere and who disappeared after obtaining answers. This point highlights the importance of ensuring that research of whatever nature leaves something behind for the benefit of the local people. It is therefore important that

results and recommendations of research are explained to the local community members once completed. These results and recommendations should be simplified to a level suitable for community member's comprehension. This would not only enhance community member's understanding of the subject that was investigated, but would also foster a good relationship between researchers and local communities.

6. CONCLUSIONS AND RECOMMENDATIONS

The significant result of this study has been the highlight of pertinent socio-economic issues governing operations and water use in small scale gardening practices. It has also been the demonstration of the use of reasonably inexpensive, but sophisticated measuring techniques to observe the soil water infiltration, redistribution and uptake in 2 dimensions. With these successful simulations, more efficient irrigation scenarios were proposed and evaluated.

It can be concluded that:

▸ Participants in small scale community gardening are predominantly women, therefore infrastructure design should consider their needs.

▸ Training and technical support should form the integral part of small scale agricultural development.

▸ Farmer managed gardens work better than those managed by external bodies.

▸ Reliable water supply for irrigation purposes is often a serious problem in small scale community gardening.

▸ Soil hydraulic properties exhibit spatial variability and inconsistent and uneven land preparation influences this variability in the soil hydraulic properties at Willowfontein and Taylors Halt.

▸ Automated tensiometers and raingauges, with simple recording of irrigation application timing and duration were critical for the observation and definition of soil water processes in small scale irrigation.

▸ The effects of over irrigation, infrequent or too frequent application were easily detectable by evaluating the record of matric pressure head data at different depths.

▸ Simulation of the soil matric pressure head history faithfully reproduced the dominant effects of the current irrigation practice.

▸ Once the model had been successfully verified against the observed data, scenarios of more efficient application were produced and the soil water processes evaluated.

▸ At Willowfontein, a more frequent application of smaller amounts of furrow irrigation was found to lead to a more efficient use of water, resulting in a reduction in drainage below the root zone of 115 mm of water over a period of one month.

▸ At Taylors Halt, a less frequent application of similar amounts of hand irrigation was found to be a more efficient use of the water, resulting in a reduction in drainage below the root zone of 80 mm over a period of one month.

6.1 Recommendations for future research

The research work presented in this document is possibly one of the first studies of this kind and intensity to be carried out in South Africa under developing conditions. For this reason no logical guidelines could be adhered to in terms of the methodology of information gathering on pertinent socio-economic issues and on the setup of the experiment. In retrospect, with regard to information gathering on socio-economic issues, recommendations are that, in addition to the suggestions in section 5.2:

▸ Questionnaires be circulated to all the members of the gardening group or the cultivators, and not only the group leaders as was the case in this study. This would allow a broader cross-section of ideas to be expressed, thereby eliminating bias, and

▸ Questionnaires should not only be designed for community garden participants, but should also involve other local community members who are not members of the gardening group.

Owing to the nature of this study, which did not only focus on scientific issues pertinent to small

scale community garden type irrigation, but also established socio-economic issues relevant to the development of small scale agriculture, recommendations are made below on the areas that need further investigation towards the development of this agricultural sector:

▸ A study should be commissioned that would investigate appropriate markets for the sale of community garden produce, existing blockages to new entrants, quality and quantity of produce, production efficiency levels required and possible synergies that could be adopted by community gardeners in order to achieve these efficiencies. A study of this nature is essential since community gardeners measure their success by the amount of income generated from the sale of their produce. Currently they are frustrated by the inability to sell all the produce they set aside for sale.

Resulting from the observations and simulations of this study, it is recommended that:

▸ The results are communicated to the Willowfontein and Taylors Halt gardening communities and others involved with similar practices.

▸ The developed methodology is used to assess the efficiencies of sprinkler irrigation systems that are being promoted and installed by the Department of Agriculture for community gardeners. This recommendation is made in the understanding that water application efficiencies are important in the context of a water scarce country like South Africa, particularly since the establishment of community gardens is a rapidly growing land use.

▸ The feasibility of the use of automated soil sensors or other simpler devices in small scale agriculture is persued with the purpose of optimizing irrigation plant water uptake and source water use.

▸ The use of simulation modelling be recommended as a tool for evaluating current practices and in devising more efficient strategies in the small scale irrigation industry.

6.2 Recommendations for successful operation of a community garden

A number of lessons have been learnt on successful operation of a community garden from carrying out this study. These lessons are summarised into five points as discussed below:

- ▸ A successful community garden has a sound management structure, which manages and enforces rules decided upon by the members of the gardening group collectively,

- ▸ Rule crafting is conducted by the group members and there is a minimal or no external intervention with regard to enforcing rules governing operation of a community garden,

- ▸ The entire community garden plot is managed as a unit in terms of operations, but at sub-plot level, responsibility for cultivation, planting, irrigation, harvesting and sale of some of the produce, lies entirely with the sub-plot owner, and sub-plot owners show commitment to their gardening operations,

- ▸ Successful community gardners work collectively on sub-plots abandoned by members who give up the gardening in pursuit of alternative opportunities elsewhere, and

- ▸ Successful community gardners do not wait for donor funding to solve all their problems, but develop innovative ways of solving their problems, e.g. establish stalls to sell their produce and contributing funds towards hiring transport to sell their produce outside their community.

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APPENDIX A

Calibration equations for all pressure transducers to convert electronic signal (mV) to a corresponding capillary pressure head (m).

Willowfontein	Transducer Number	Regression Equation
Nest 1	AE 6	(-40.19-80+0.27587(V))/100
	AE 8	(-40.19-54+0.27587(V))/100
	AE 10	(-54.85-38+0.27662(V))/100
Nest 2	AE 13	(-56.24-95+0.27624(V))/100
	AE 15	(-89.99-60+0.2007(V))/100
	AE 17	(-47.25-42+0.2762(V)/100
Nest 3	AE 9	(-54.85-96+0.27662(V))/100
	AE 12	(-54.39-57+0.27641(V))/100
	AE 19	(-47.52-35+0.27591(V))/100
Nest 4	AE 11	(-56.15-83+0.2765(V))/100
	AE 14	(-41.46-56+0.27597(V))/100
	AE 16	(-55.29-35+0.27641(V))/100

Taylors Halt	Transducer Number	Regression Equation
Nest 1	TH 7	(-47.47-41+0.2776(V))/100
	TH 8	(-46.40-77+0.2787(V))/100
	TH 9	(-39.29-91+0.2770(V))/100
Nest 2	TH 4	(-45.02-47+0.2767(V))/100
	TH 2	(-44.40-83+0.2768(V))/100
	TH 6	(-40.77-116+0.2781(V))/100
Nest 3	TH 1	(-42.33-51+0.2772(V))/100
	TH 5	None
	TH 3	(-45.93-118+0.2769(V))/100
Nest 4	TH 10	(-41.54-39+0.2773(V))/100
	TH 11	(-43.19-77+0.2772(V))/100
	TH 12	(-41.87-106+0.2773(V))/100

APPENDIX B

The tables below give information relating to the tensiometer and transducer number with tensiometer lengths and depths below the soil surface for each tensiometer nest used at Willowfontein and Taylors Halt. The transducer number is related to the equations shown in Appendix A

Willowfontein	Tensiometer Number	Transducer Number	Tensiometer Length (mm)	Depth Below Soil Surface (mm)
Nest 1	AE 6	AE 6	800	550
	AE 8	AE 8	540	390
	AE 10	AE 10	380	180
Nest 2	AE 13	AE 13	950	720
	AE 15	AE 15	600	370
	AE 17	AE 17	420	190
Nest 3	AE 9	AE 9	960	730
	AE 12	AE 12	570	330
	AE 19	AE 19	350	110
Nest 4	AE 11	AE 11	830	580
	AE 14	AE 14	560	290
	AE 16	AE 16	350	160

Taylors Halt	Tensiometer Number	Transducer Number	Tensiometer Length (mm)	Depth Below Soil Surface (mm)
Nest 1	TH7	TH7	410	200
	TH 8	TH 8	770	470
	TH 9	TH 9	910	720
Nest 2	TH 4	TH 4	470	200
	TH 2	TH 2	830	490
	TH 6	TH 6	1160	830
Nest 3	TH 1	TH 1	510	260
	TH 5	TH 5	830	430
	TH 3	TH 3	1180	800
Nest 4	TH 10	TH 10	390	200
	TH 11	TH 11	770	570
	TH 12	TH 12	1060	860

APPENDIX C

(a) Hydraulic conductivity measured at the soil surface at Willowfontein

Willowfontein	Capillary pressure head (mm)	Unsaturated hydraulic conductivity (mm/h)
Nest 1	5	133.20
	50	57.60
	150	50.40
Nest 2	5	12.60
	50	5.76
	150	4.68
Nest 3	5	4.32
	50	1.73
	150	1.04
Nest 4	5	4.32
	50	2.41
	150	1.82

(b)   Hydraulic conductivity measured at the soil surface at Taylors Halt

Taylors Halt	Capillary pressure head (mm)	Unsaturated hydraulic conductivity (mm/h)
Nest 1	5	23.76
	95	12.6
	165	7.2
	215	6.48
Nest 2	5	12.24
	95	7.92
	165	6.48
	215	6.48
Nest 3	5	14.76
	95	7.56
	165	3.6
	215	2.52
Nest 4	5	13.32
	95	6.84
	165	5.4
	215	4.68

(c)   Hydraulic conductivity measured down the soil profile at Willowfontein

Willowfontein (PIT)	Capillary pressure head (mm)	Unsaturated hydraulic conductivity (mm/h)	Saturated hydraulic conductivity (mm/h)
Surface	0		24.58
	5	12.6	
	50	5.76	
	150	4.68	
Depth = 300 mm	0		12.66
	15	8.96	
	55	5.76	
	105	6.12	
Depth = 760 mm	0		12.66
	5	8.64	
	50	3.24	
	150	2.52	
Depth = 1300 mm	0		9.54
	5	2.45	
	25	1.15	
	45	1.04	

(d) Hydraulic conductivity measured down the soil profile at Taylors Halt

Taylors Halt (Pit)	Capillary pressure head (mm)	Unsaturated hydraulic conductivity (mm/h)	Saturated hydraulic conductivity (mm/h)
Surface	0		131.70
	5	5.04	
	95	2.88	
	165	1.87	
	215	1.80	
Depth = 320 mm	5	6.05	
	95	3.90	
	165	2.36	
Depth = 890 mm	0		1406.55
	5		
	95		
	165		
	215		
Depth = 1070 mm	0		7.93
	5		
	95		
	165		
Depth = 2000 mm	5	1.94	
	95	0.66	
	165	0.38	

APPENDIX D

Example of hydraulic conductivity and water retention characteristic curve fitting procedure using van Genuchten (1980) parameters. Shown is the water content and matric potential values derived from the controlled outflow cell. The selected water content (Se) values, water contents, pressure heads and hydraulic conductivities simulated using van Genuchten (1980) equations are also shown.

Taylors Halt - Surface

Taylors Halt		(Nest 1)		
Surface Tension (h) (mm)	Conductivity K(h) (mm/s)		Conductivity K(h) (mm/h)	
0.01	0.0038594		13.17024	13.17024
5	1.4E-03		5.04	
95	8.0E-04		2.89	
185	5.2E-04		1.872	
215	5.0E-04		1.0	
0.01		1.301E+01		
0.1		1.288E+01		
1		1.160E+01		
3		1.081E+01		
5		9.915E+00		
7		9.389E+00		
9		8.903E+00		
16		8.703E+00		
20		7.133E+00		
50		4.553E+00		
80		3.148E+00		
100		2.520E+00		
1000		2.013E-02		

Burette (ml)	Ch1 (mV)	Meas.MPH (mm)	Se	Water content (mm^3/mm^3)	Sim.MPH (mm)			
41.7	-23.0	0.1		0.661		Wet mass	182.94	g
39.8	-18.5	35		0.661		Dry mass	137.77	g
34.1	-17.4	58		0.661		Tare	77.64	g
33.0	-16.6	64		0.661		Extra	5.15	g
32.0	-9.3	137		0.554		Ex tare	4.33	g
30.4	8.3	313		0.530		Bulk Density	897	g/mm^3
28.1	38.9	599		0.496		Porosity	0.661	mm^3/mm^3
27.5	54.8	778		0.497		Final W.C.	0.375	mm^3/mm^3
26.0	161.7	1247		0.485				
23.7	228.0	2510		0.431				
21.5	342.1	3851		0.391				
21.1	376.0	3900		0.393				
19.9	573.7	5967		0.375				

Se	Water content	Sim.MPH		Parameter	Value	
1	0.661	0		n	1.5	
0.96	0.64616	73		n-1	0.5	
0.92	0.63132	124		m	0.333	
0.88	0.61648	172		Ks	13.17024	mm/h
0.84	0.60164	222		Alpha	0.0035	mm^-1
0.8	0.5868	277		Thetas	0.661	
0.76	0.57196	338		Thetar	0.29	
0.72	0.55712	404				
0.68	0.54228	480				
0.64	0.52744	570				
0.6	0.5126	675				
0.56	0.49776	801				
0.52	0.48292	955				
0.48	0.46808	1147				
0.44	0.45324	1391				
0.4	0.4384	1709				
0.36	0.42356	2135				
0.32	0.40872	2729				
0.28	0.39388	3591				
0.24	0.37904	4914				
0.2	0.3642	7105				
0.16	0.34936	11130				
0.12	0.33452	19818				
0.08	0.31968	44628				
0.04	0.30484	178564				

APPENDIX E

The data below shows the hydraulic conductivity and water retention curves for both sites

Willowfontein
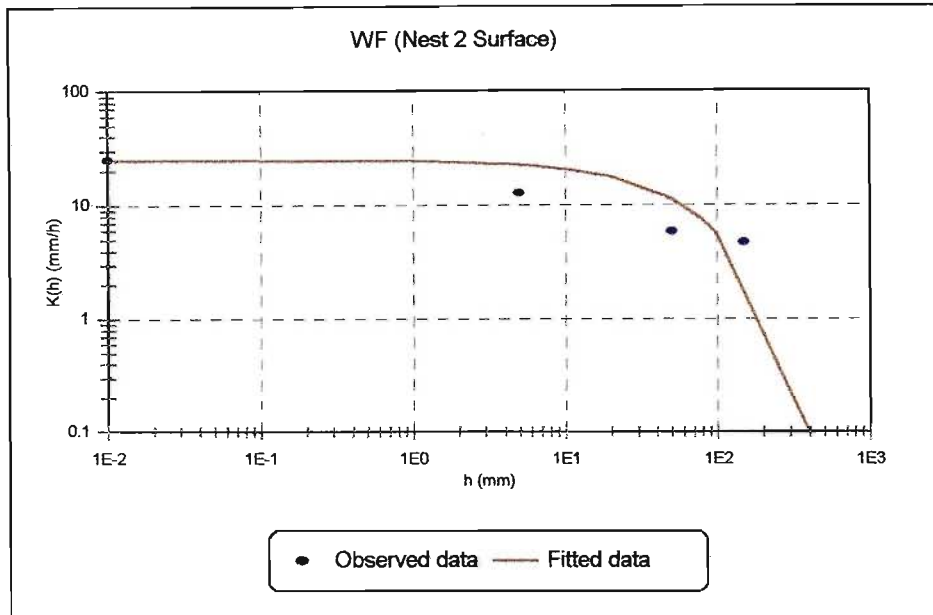
Figure E1   Hydraulic conductivity as a function of h at the soil surface at Nest 2 at
Willowfontein
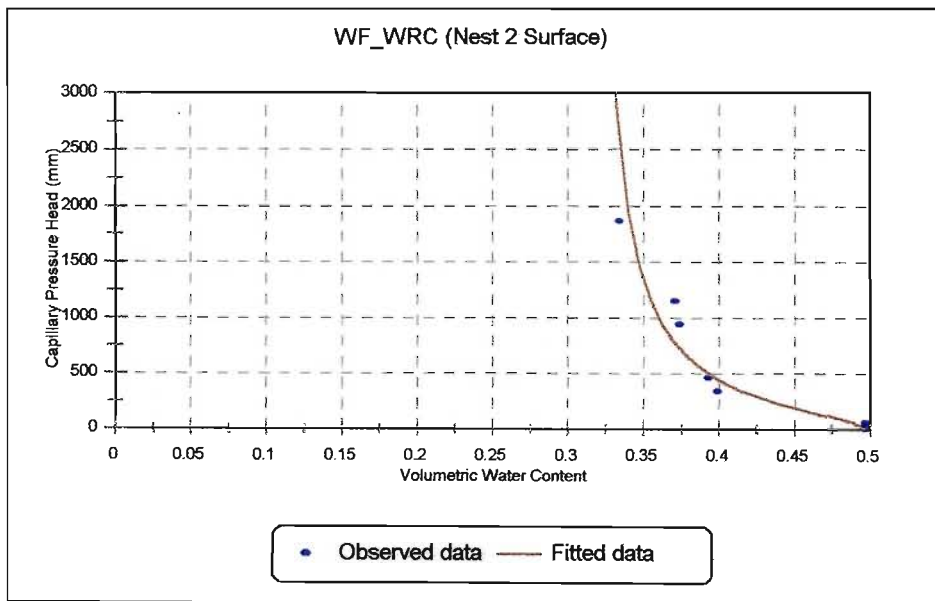
Figure E2   Water retention characteristic curve for the soil surface at Nest 2 at
Willowfontein
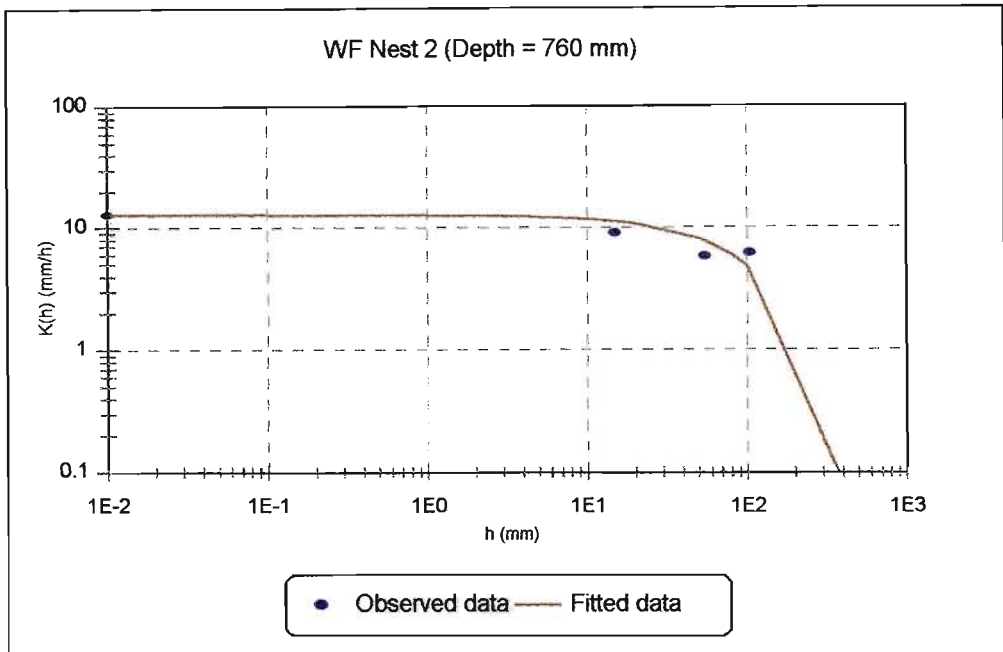
Figure E3   Hydraulic conductivity curve as a function of h for the 760 mm depth at Nest 2 at Willowfontein
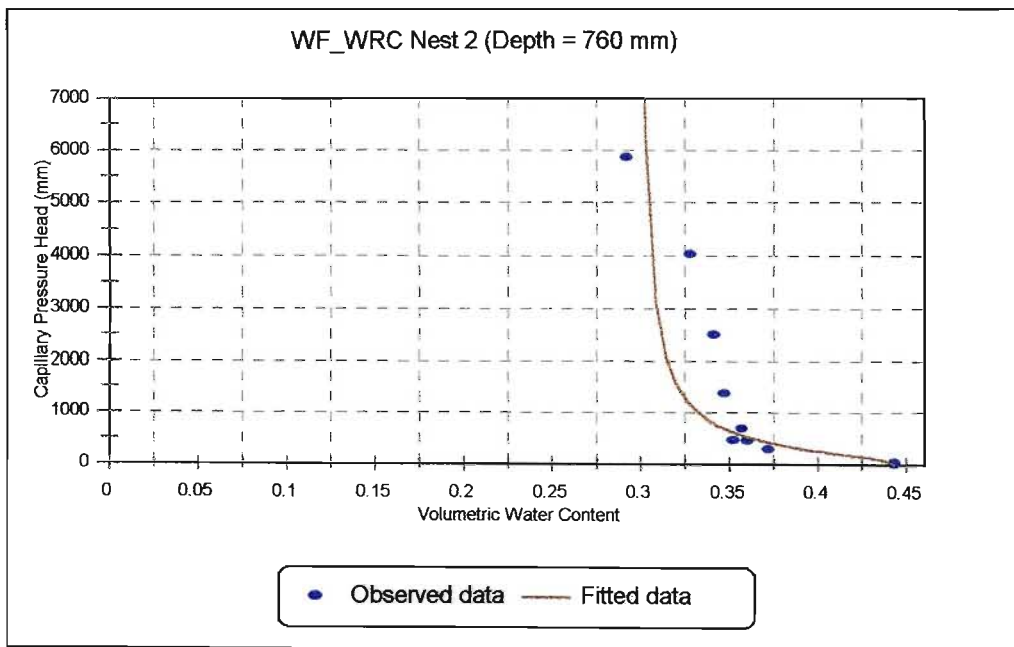
Figure E4   Water retention characteristic curve for the 760 mm depth at Nest 2 at Willowfontein
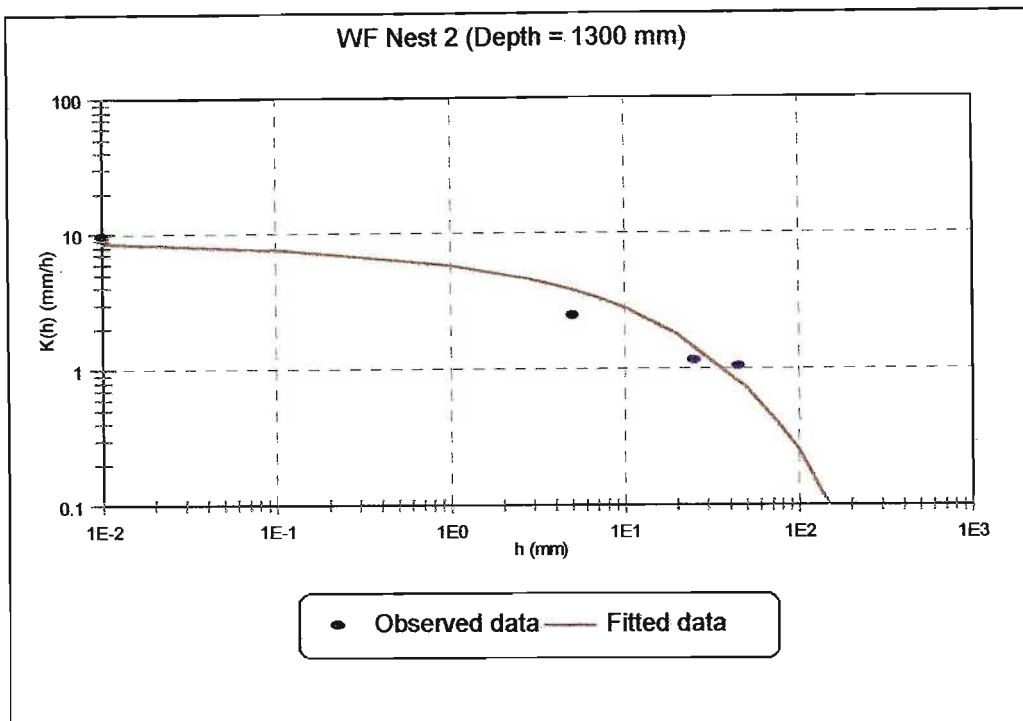
Figure E5   Hydraulic conductivity as a function of h for the 1300 mm depth at Nest 2 at Willowfontein
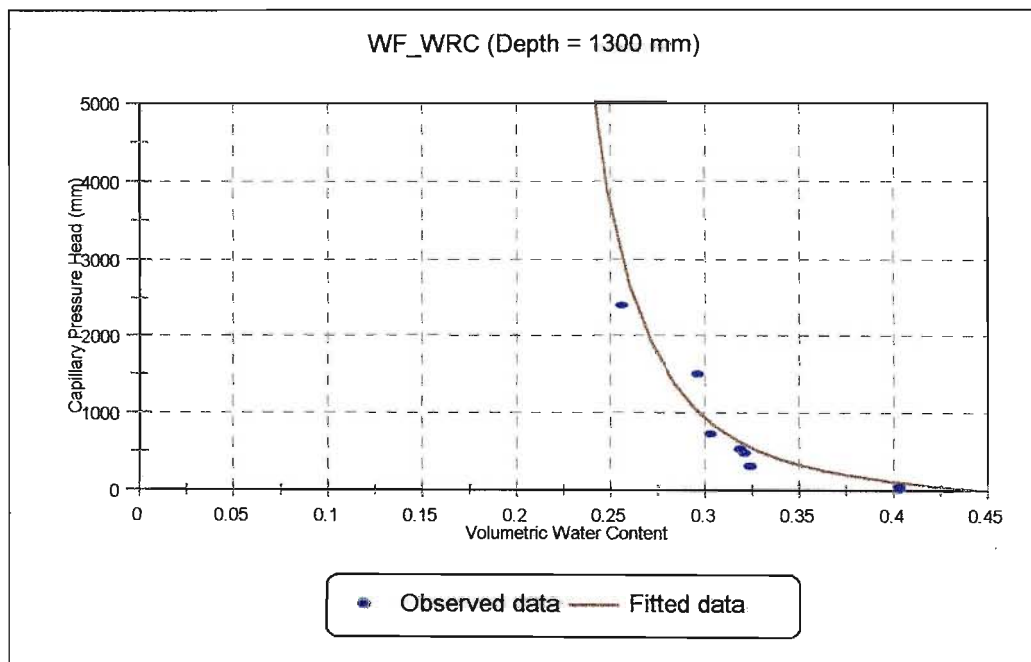
Figure E6   Water retention characteristic curve for the 1300 mm depth at Nest 2 at Willowfontein
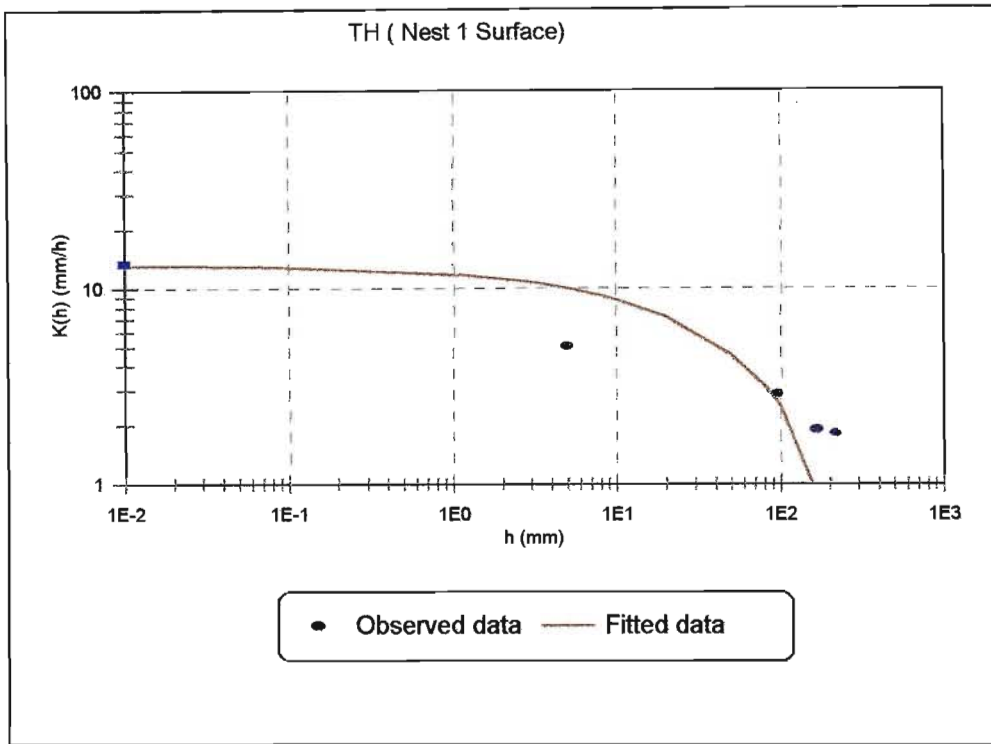
Taylors Halt

Figure E7   Hydraulic conductivity as a function of h at the soil surface at Nest 1 at Taylors Halt
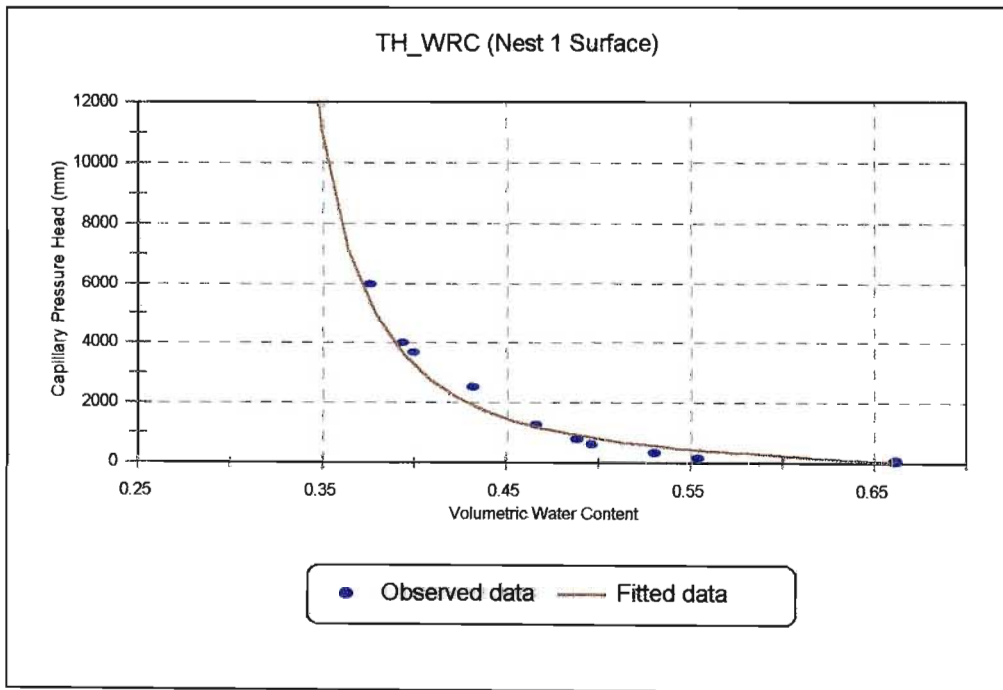
Figure E8   Water retention characteristic curve for the soil surface at Nest 1 at Taylors Halt
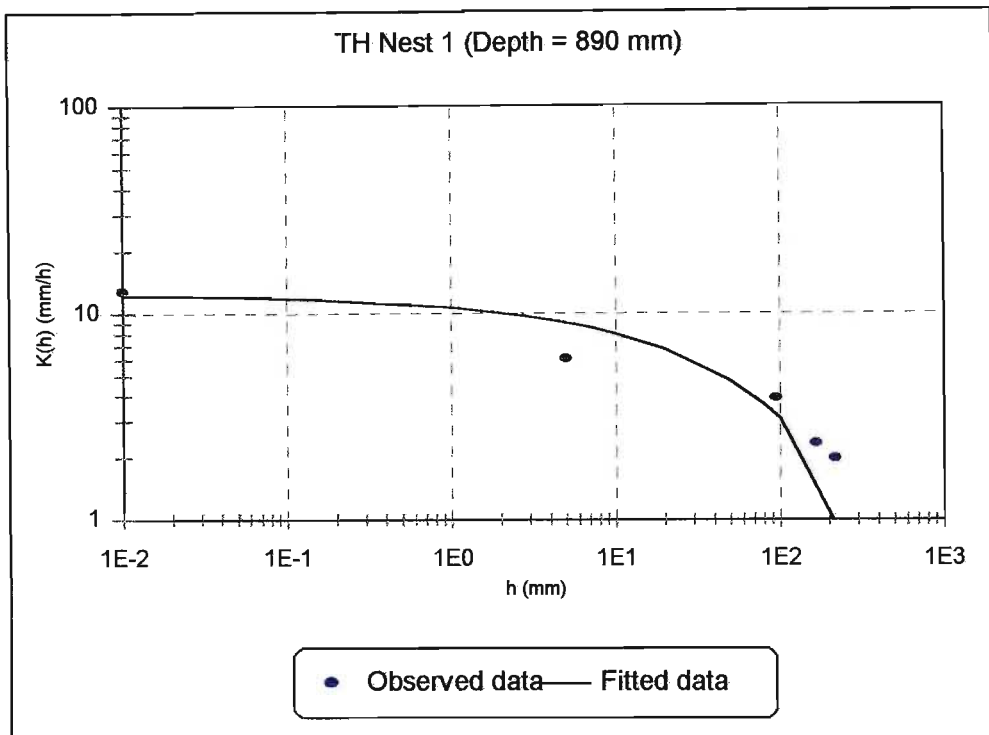
Figure E9   Hydraulic conductivity as a function of h for the 890 mm depth at Nest 1 at Taylors Halt
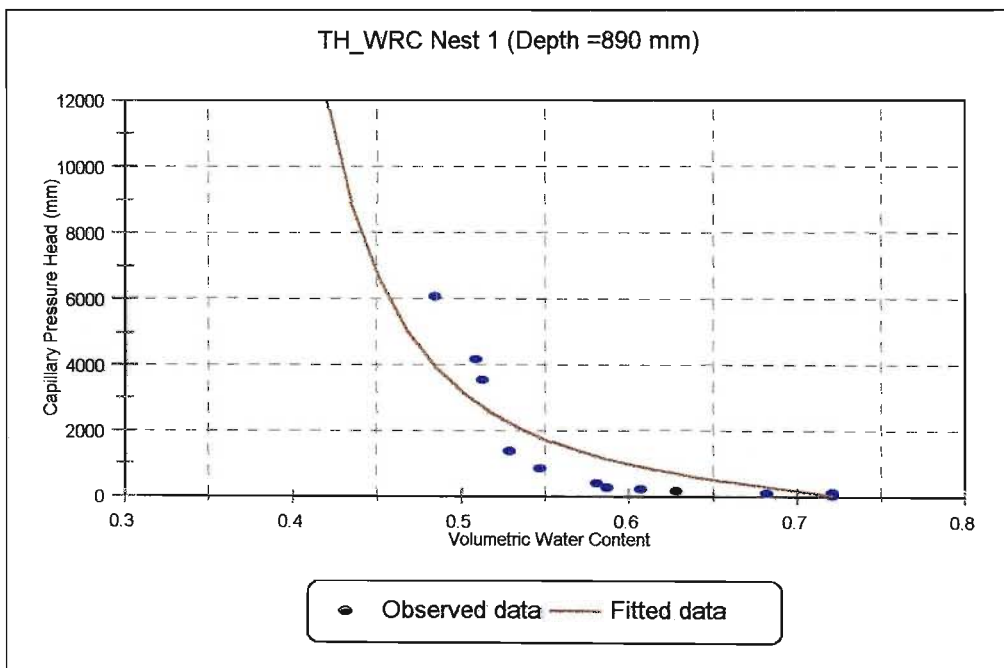
Figure E10   Water retention characteristic curve for the 890 mm depth at Nest 1 at Taylors Halt

TH Nest 1 (Depth = 1060 mm)
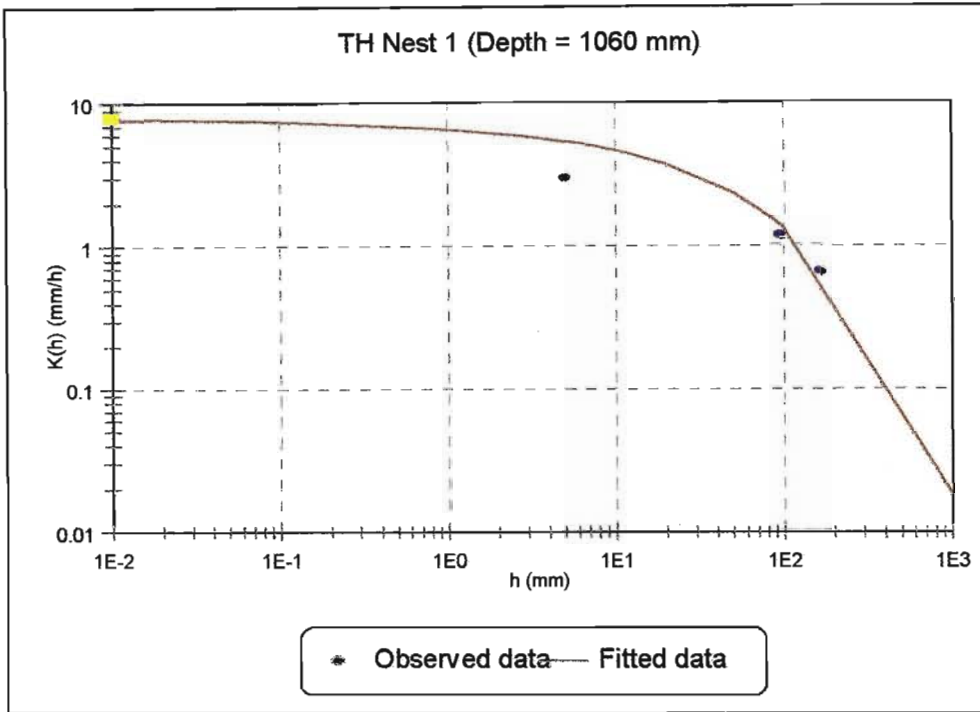
Figure E11   Hydraulic conductivity as a function of h for the 1060 mm depth at Nest 1 at Taylors Halt

TH_WRC Nest 1(Depth = 1060 mm)
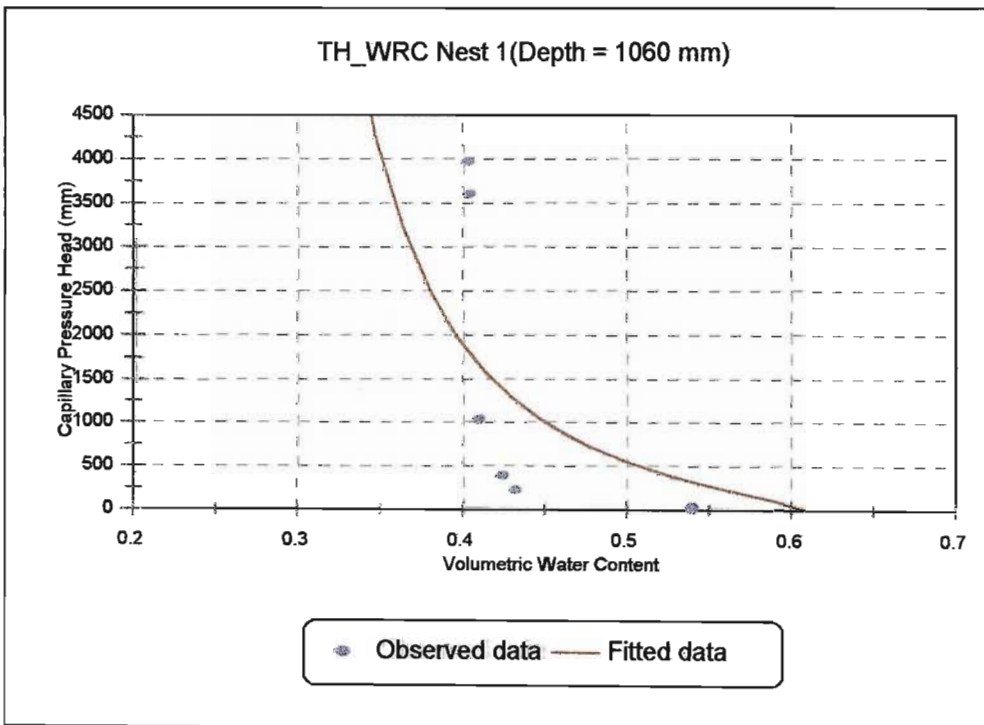
Figure E12   Water retention characteristic curve for the 1060 mm depth at Nest 1 at Taylors Halt

APPENDIX F

Willowfontein

Tensimeter, Rainfall and Irrigation data
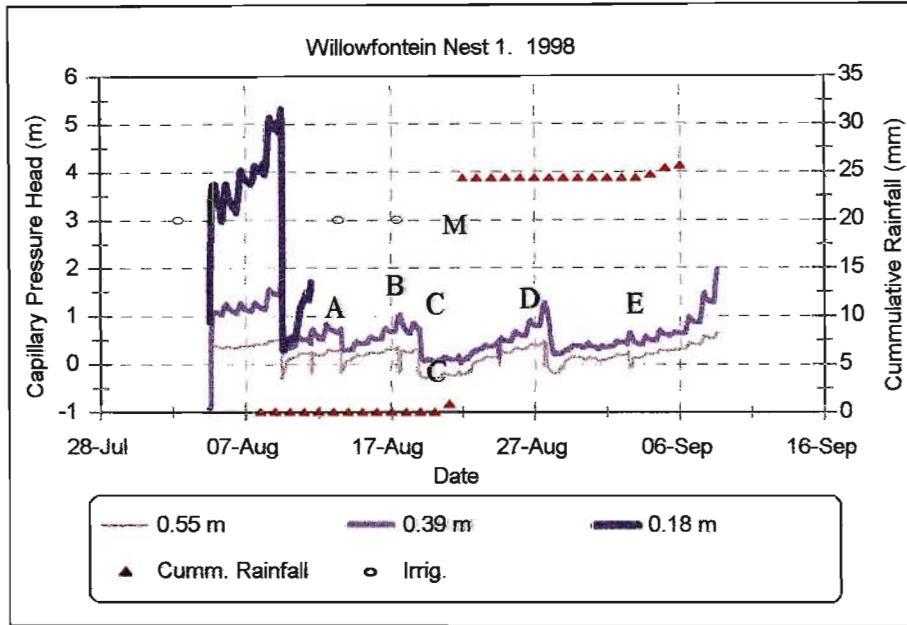
Figure F1   Tensiometer, rainfall and irrigation data for the period Aug-Sept at Nest 1 at Willowfontein.
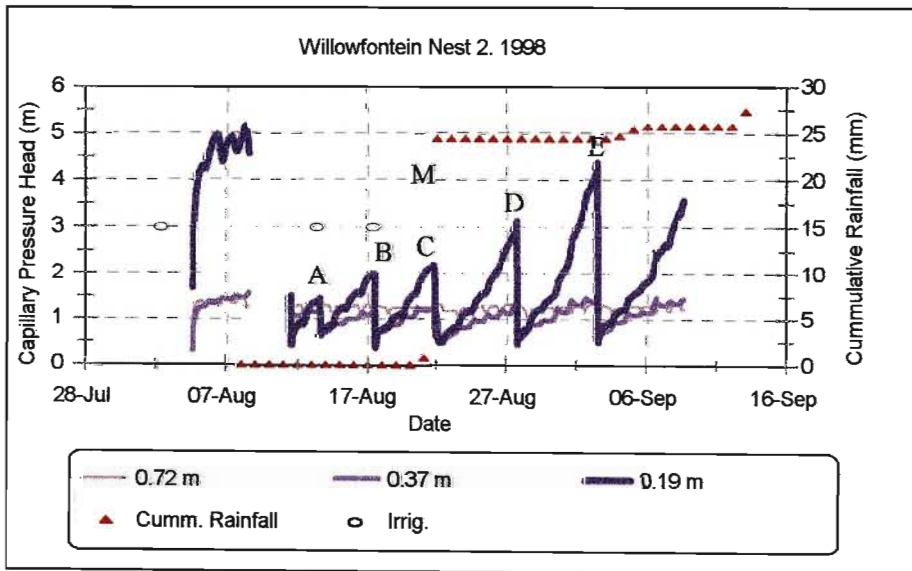
Figure F2   Tensiometer, rainfall and irrigation data for the period Aug-Sept at Nest 2 at Willowfontein
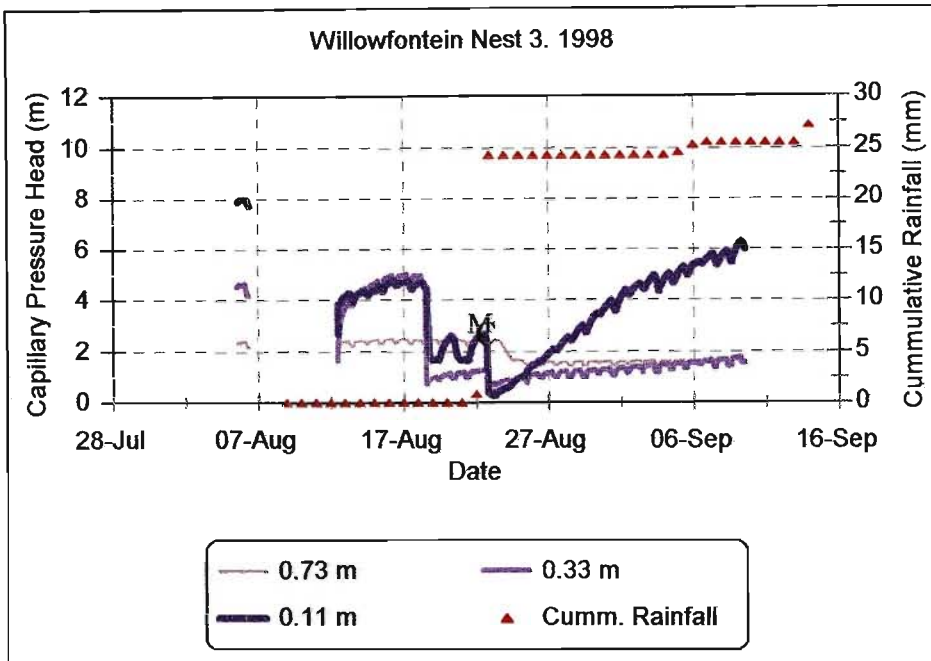
Figure F3   Tensiometer and rainfall data for the period Aug-Sept at Nest 3 at
Willowfontein
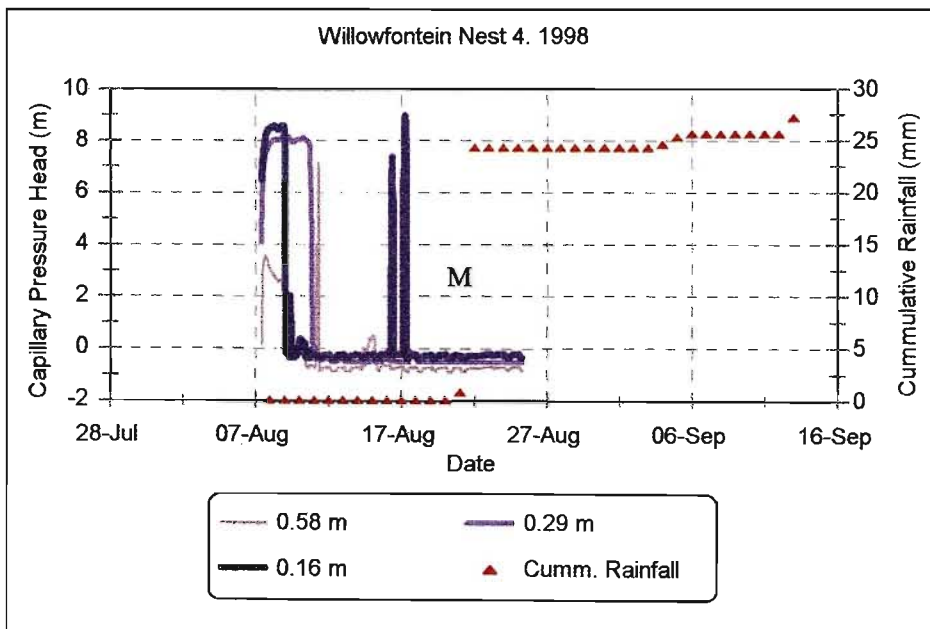
Figure F4   Tensiometer and rainfall data for the period Aug-Sept at Nest 4 at
Willowfontein
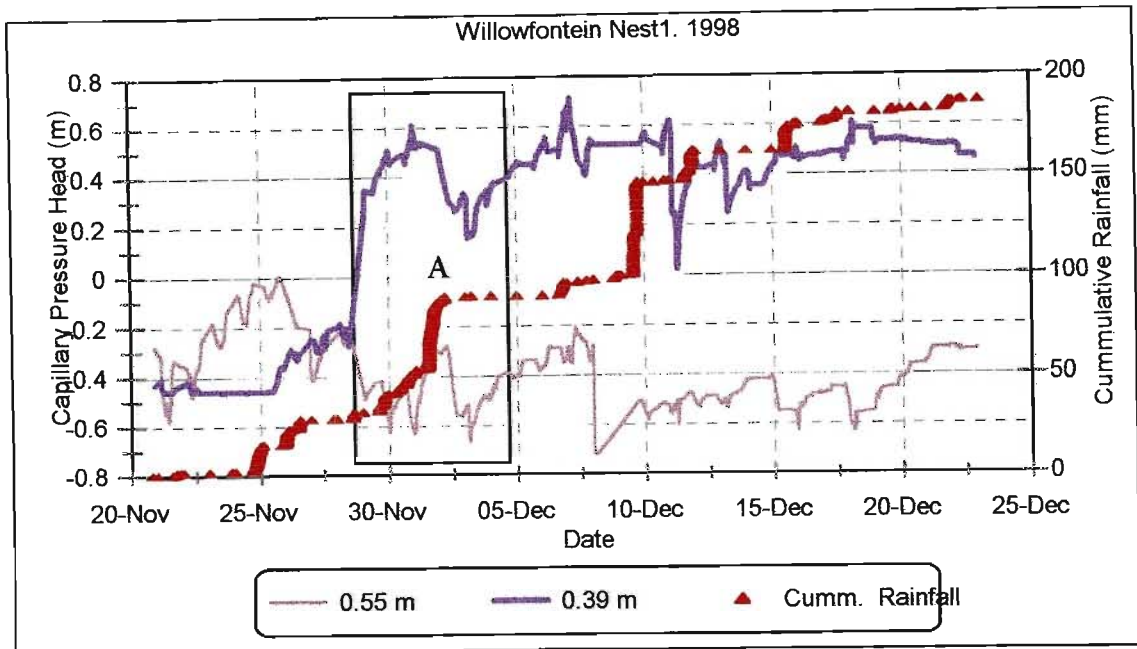
Figure F5   Tensiometer and rainfall data for the period Nov-Dec at Nest 1 at
             Willowfontein
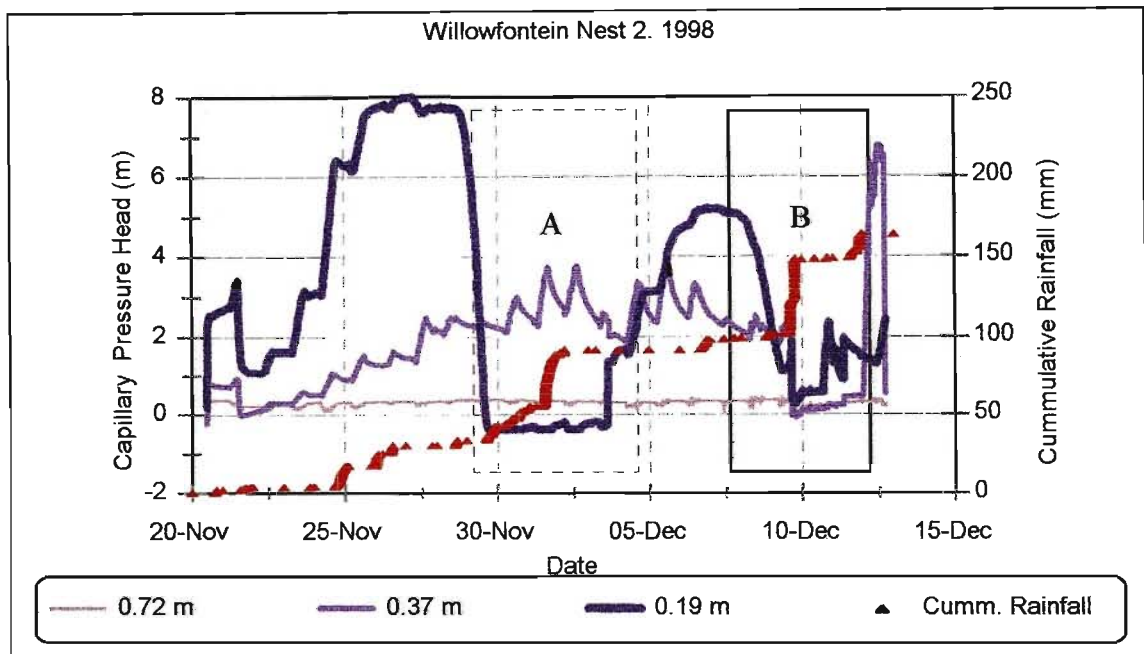
Figure F6   Tensiometer and rainfall data for the period Nov-Dec at Nest 2 at
             Willowfontein
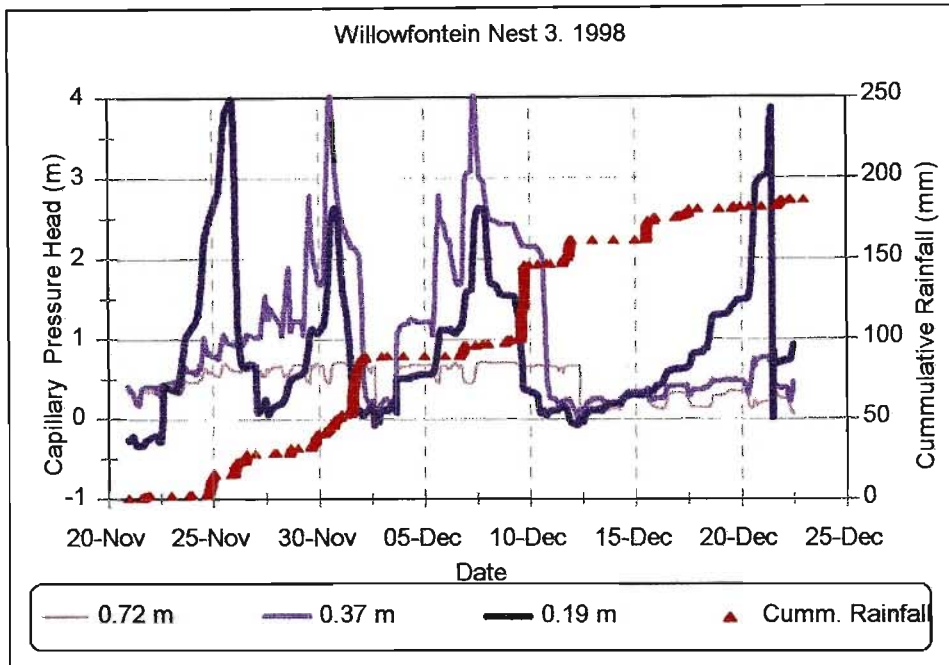
Figure F7   Tensiometer and rainfall data for the period Nov-Dec at Nest 3 at Willowfontein
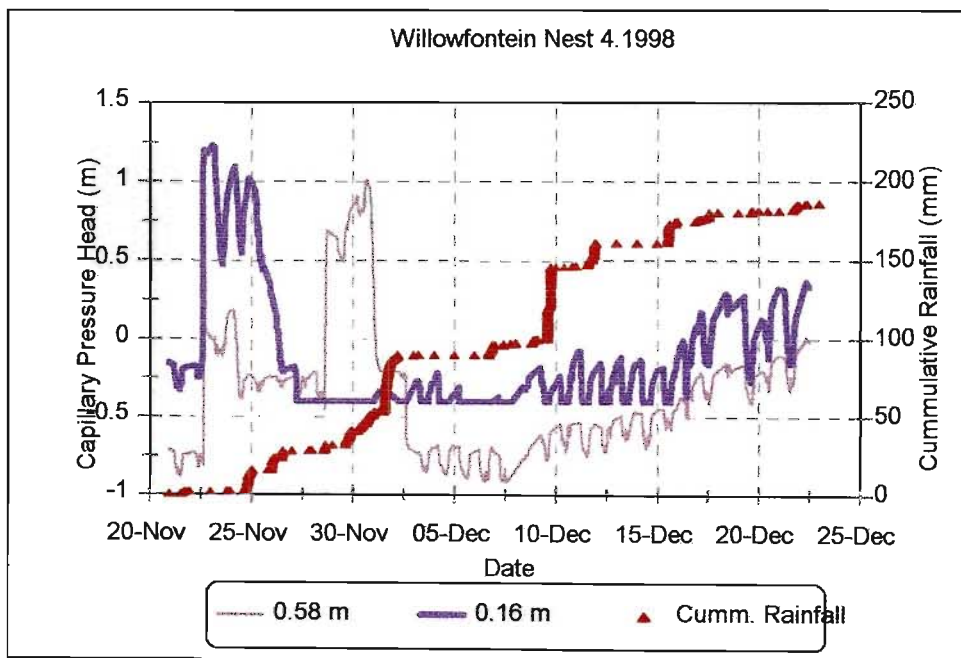
Figure F8   Tensiometer and rainfall data for the period Nov-Dec at Nest 4 at Willowfontein
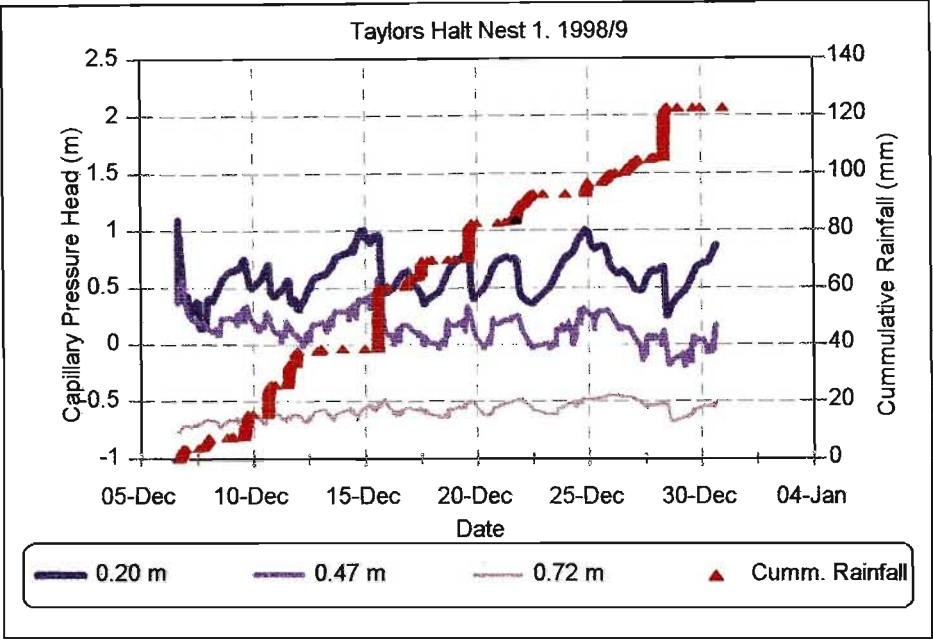
Taylors Halt

Figure F13   Tensiometer and rainfall data for the month of December at Nest 1 at Taylors
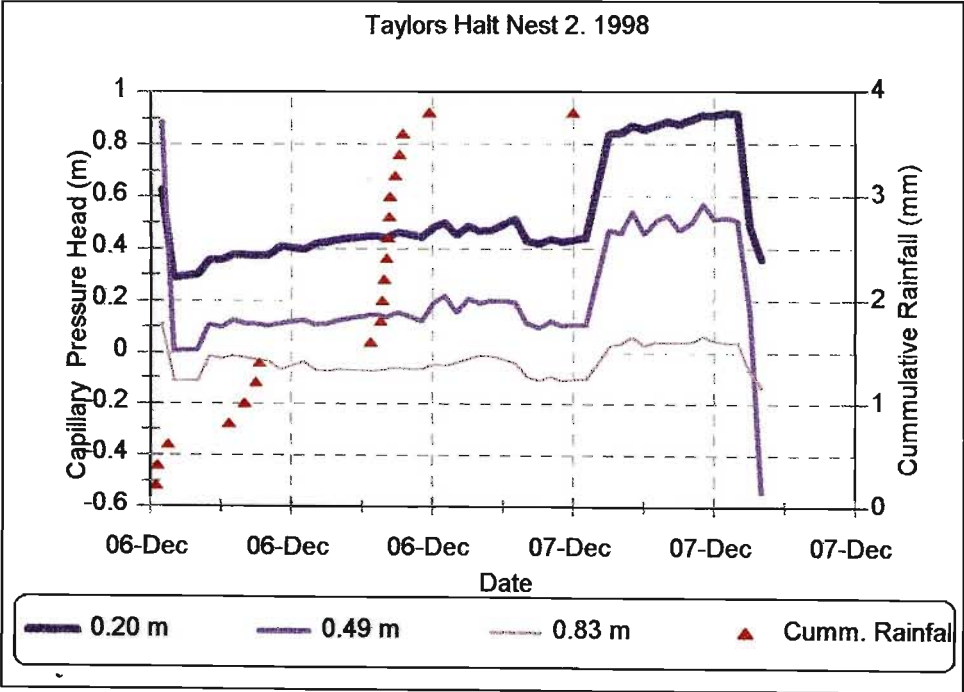
Figure F14   Tensiometer and rainfall data recorded in December for Nest 2 at Taylors Halt
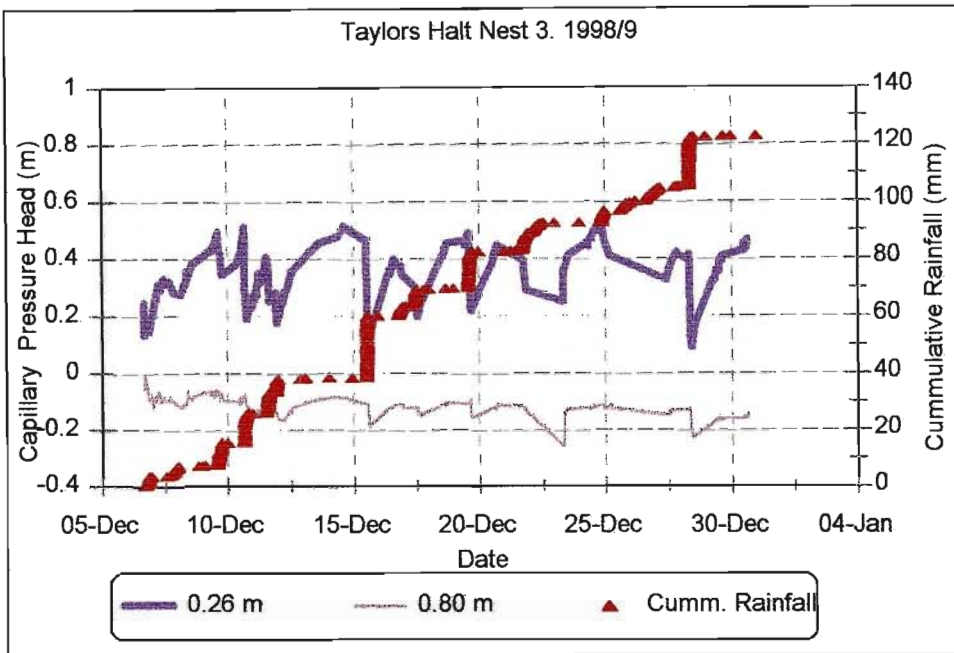
Figure F15   Tensiometer and rainfall data for the month of December at Nest 3 at Willowfontein
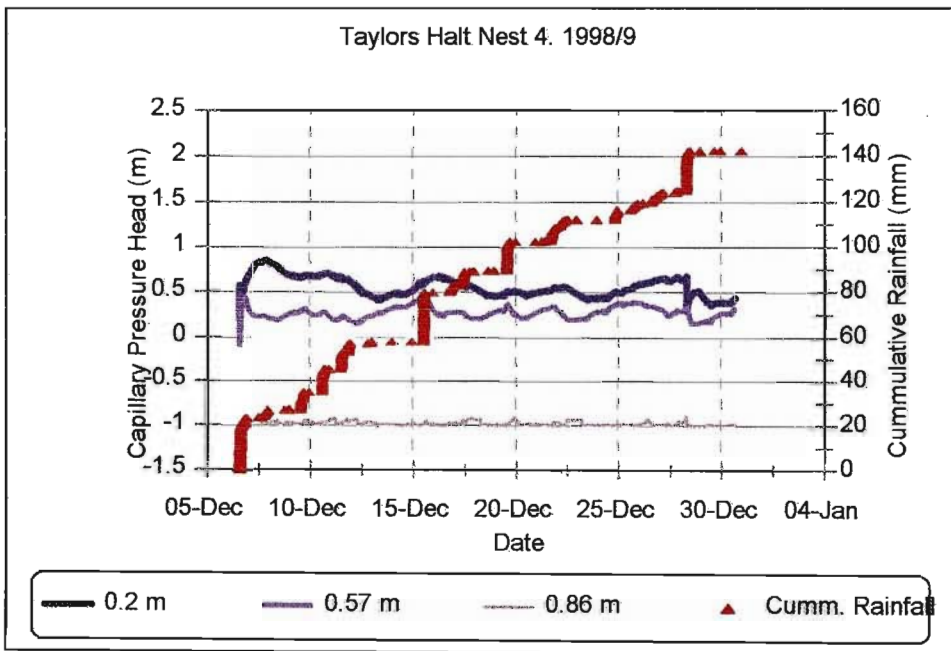
Figure F16   Tensiometer and rainfall data for the month of December at Nest 4 at Taylors Halt
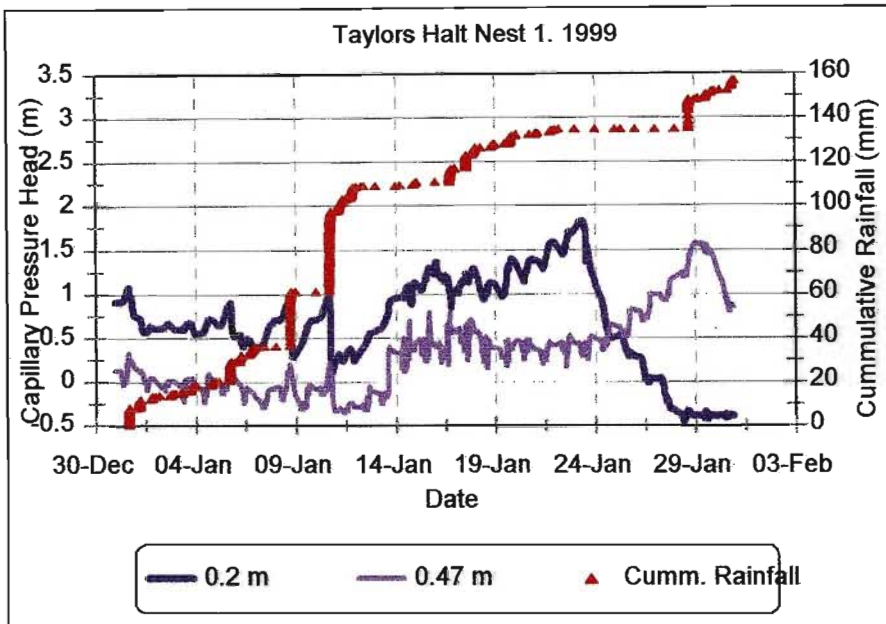
Figure F17   Tensiometer and rainfall data for the month of January at Nest 1 at Taylors Halt
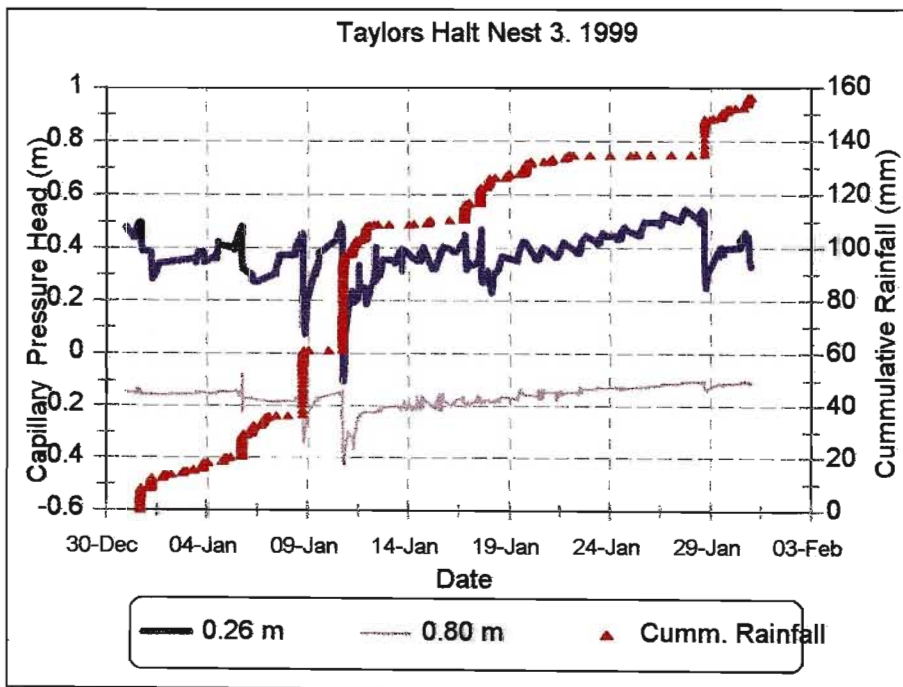
Figure F18   Tensiometer and rainfall data for the month of January at Nest 3 at Taylors Halt
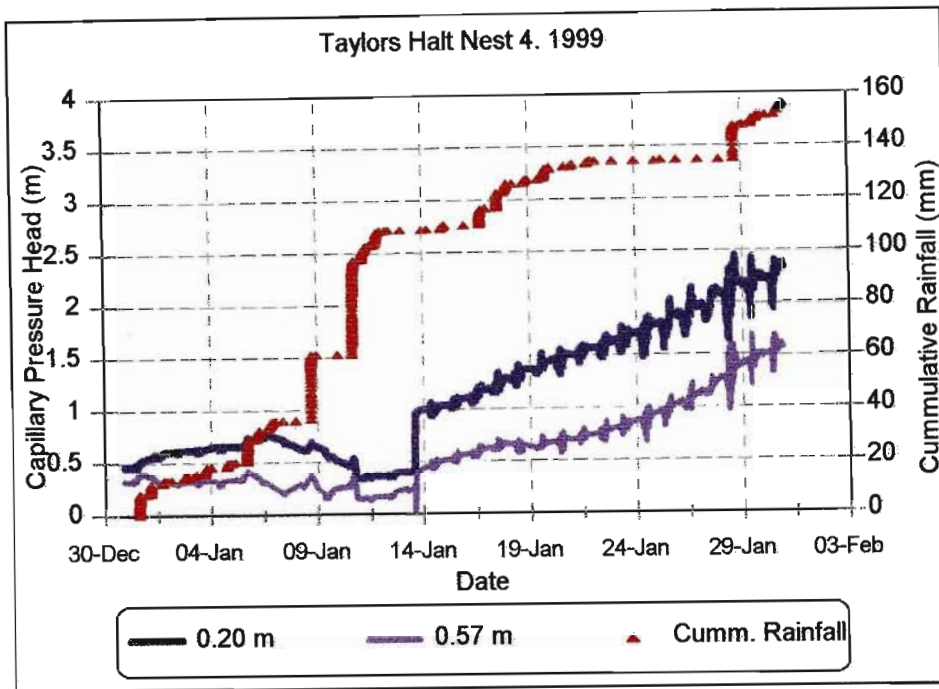
Figure F19   Tensiometer and rainfall data for the month of January at Nest 4 at Taylors
              Halt
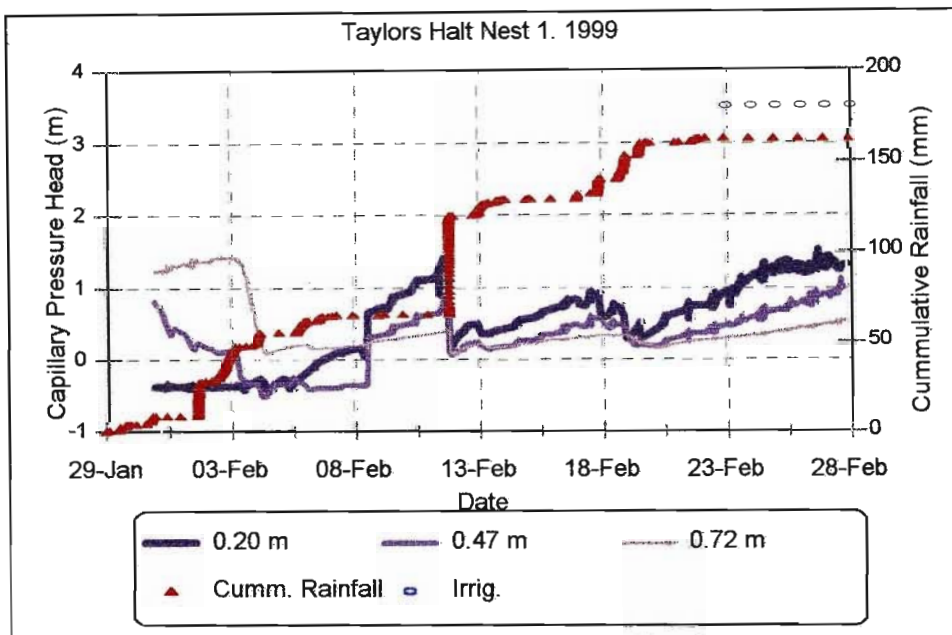
Figure F20   Tensiometer and rainfall data for the month of February at Nest 1 at Taylors
              Halt
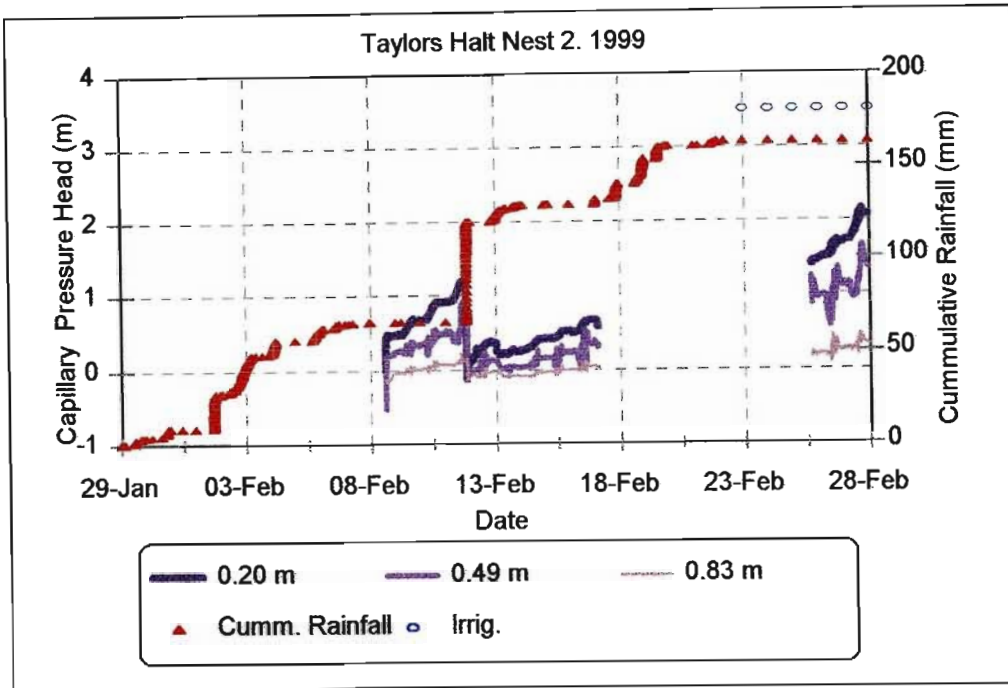
Figure F21   Tensiometer and rainfall data for the month of February at Nest 2 at Taylors
Halt
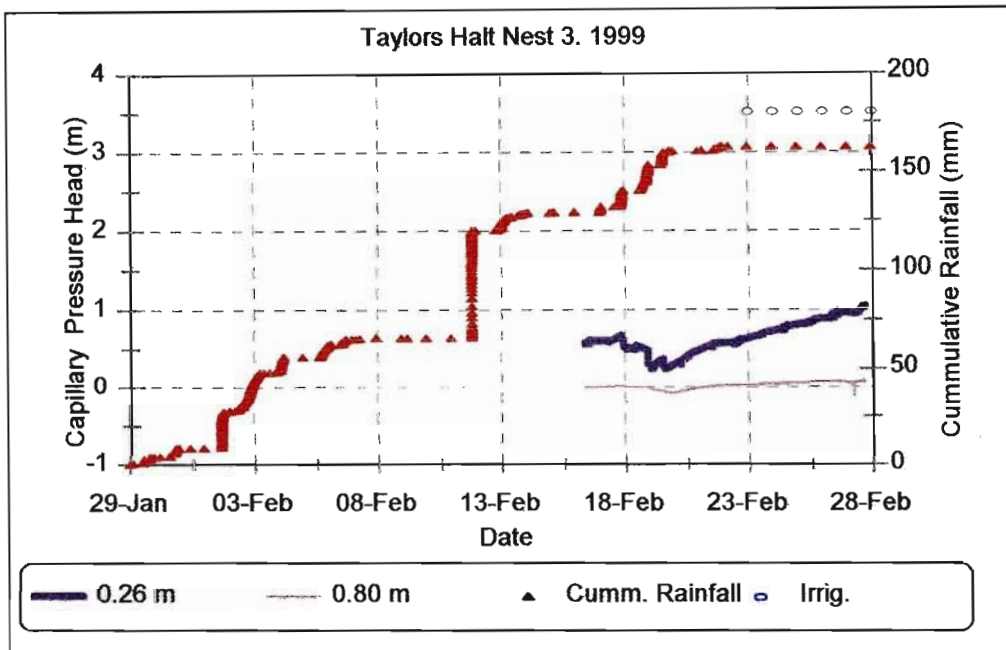
Figure F22   Tensiometer and rainfall data for the month of February at Nest 3 at Taylors
Halt
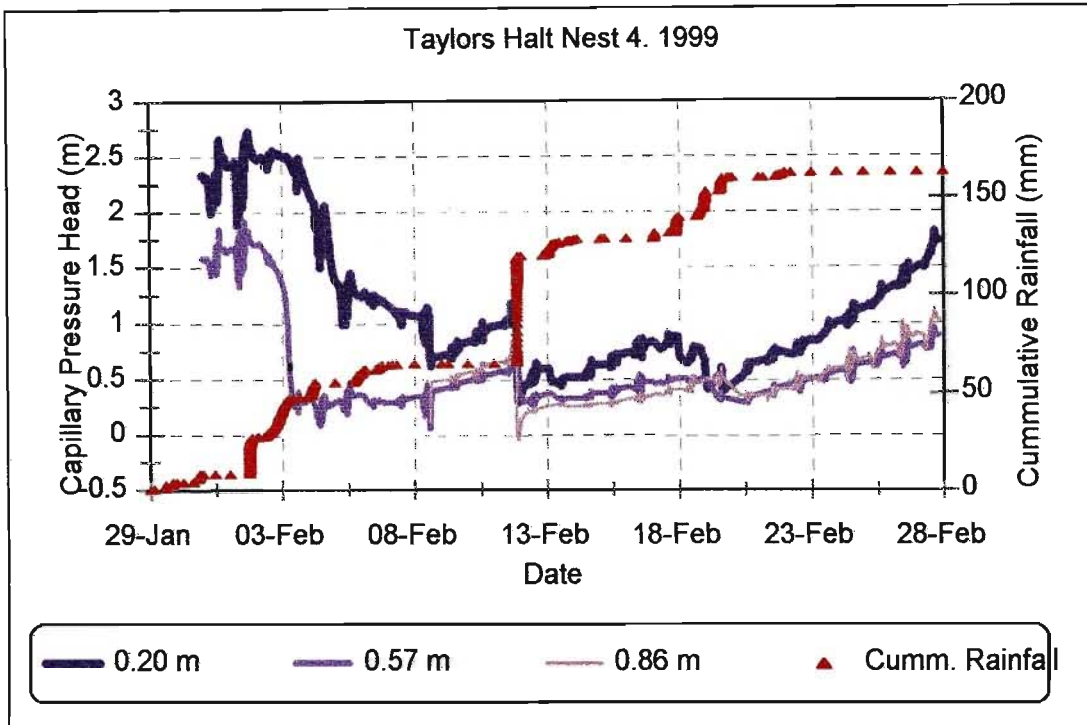
Figure F23   Tensiometer and irrigation data for the month of February at Nest 4 at Taylors
Halt
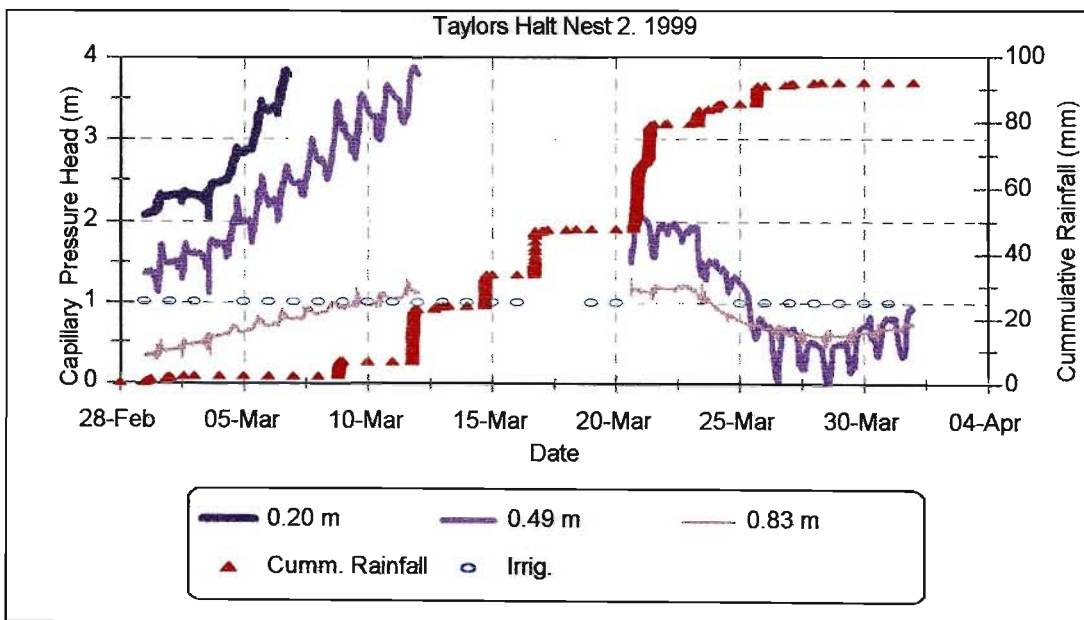
Figure F24   Tensiometer and irrigation data for the month of March at Nest 2 at Taylors
Halt
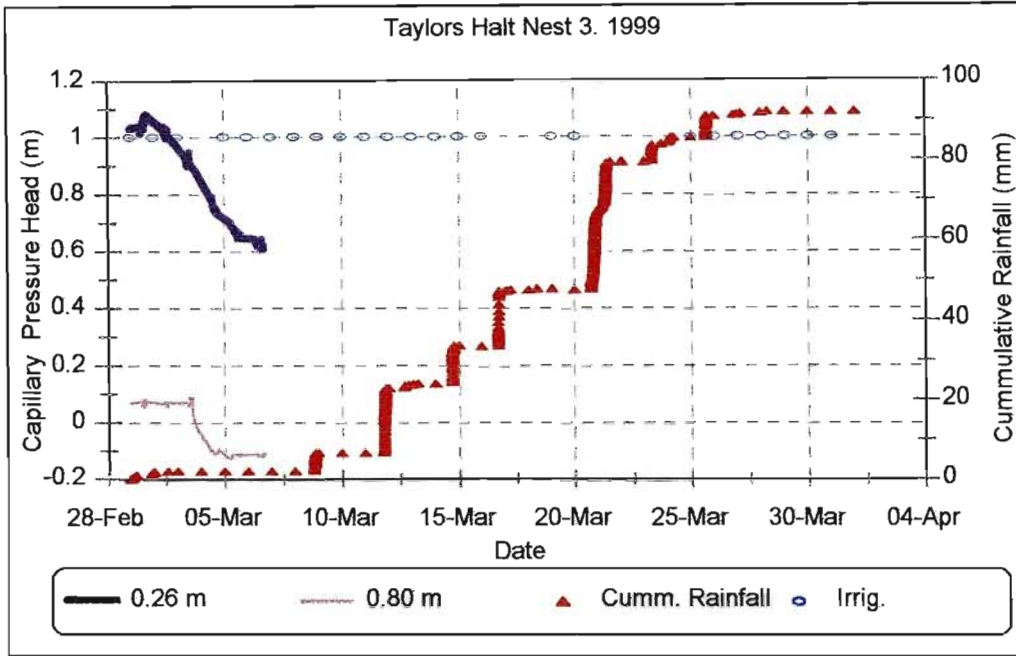
Figure F25   Tensiometer and irrigation data for the month of March at Nest 3 at Taylors Halt
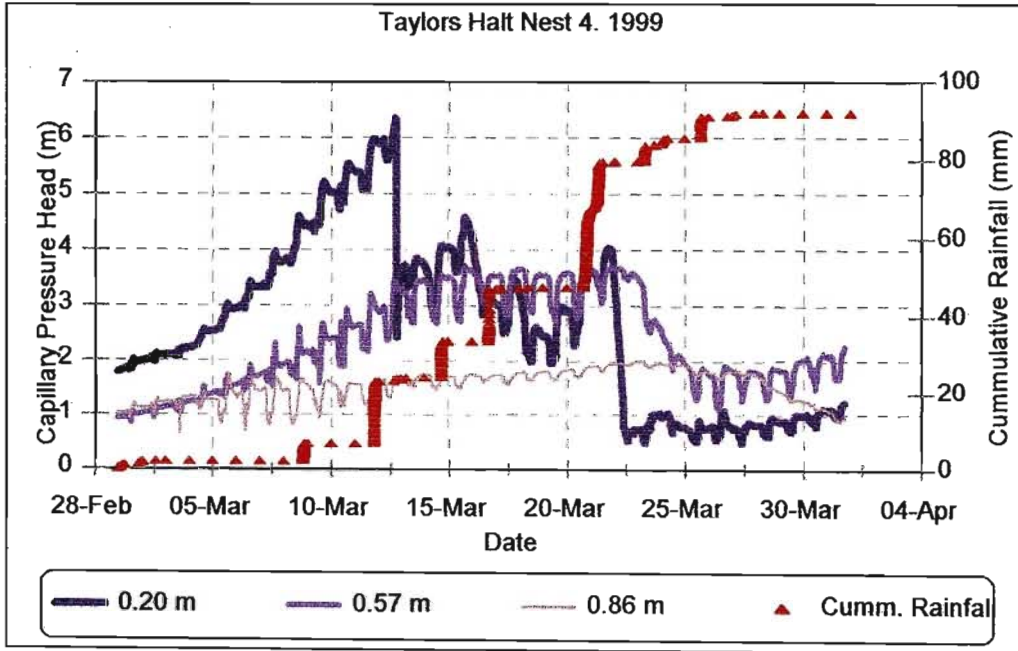
Figure F26   Tensiometer and rainfall data for the month of March at Nest 4 at Taylors Halt

APPENDIX G

Sample Questionnaire

1   History/Background Information on the gardening group

1.1   What is the name of the group ?

1.2   Why was the group given this name ?

1.3   When, why and how was the group formed ?

1.4   How many members does the group have, specify demographics ?

1.5   What are the objectives of the group ?

2   Management structure of the group

2.1   Does the group have a management structure ?

2.2   If any, what are the functions of the members within the management structure ?

2.3   What role does the management structure play with regard to the operations of the group ?

2.4   What governs the activities of the group ?

2.5   Do you meet regularly as a group, and if so, do you take minutes at these meetings and why ?

2.6   Who else besides the members of the group attend your meetings and why is it important that they attend ?

3   Land ownership and tenure system

3.1   Who owns the piece of land where gardening activity takes place ?

3.2   If not the gardening group, is there a formal land tenure arrangement in place ?

4 Garden layout and participation

4.1 How is the plot subdivided ?

4.2 Who is responsible for the allocation of sub-plots to different members of the group ?

4.3 Is there any criteria that is used in the allocation of sub-plots to different members of the group ?

4.4 Do all members work diligently on their sub-plots, if not why ?

5 Water allocation and distribution in the area

5.1 Are there any existing rules and/or patterns of water allocation and distribution in this area ?

5.2 If any, are they influenced by upstream or downstream users ?

5.3 Do you experience shortages of water in this area ?

6 In-field Irrigation

6.1 Do you ever experience any shortages of water for irrigation purposes ?

6.2 If you do, what plans do you have to solve the problem of water shortage ?

6.4 When do you irrigate and why ?

6.5 Do conflicts occur among the members of the group over irrigation water ?

6.6 Do you have a common irrigation schedule as a group or members irrigate according to their own individual schedule ?

7 Sale of produce

7.1 Which is your target market ?

7.2 How do you sell your produce ?

7.3 What constraints do you experience towards successful sale of produce ?

8   Income generation and funding

8.1   How do you generate income to cover the operational costs of the group ?

8.2   Do you have other external sources of funds ?

8.3   Should you receive external funding, do you think you have sufficient administrative capacity for those funds ?

9   Training and technical support

9.1   Have you attended any course on good agronomic practices before, and do you get enough technical support from the department of agriculture ?

9.2   Where do you think you need training ?

9.3   Where do you think you need ongoing support and in your view who should provide that support ?

10   Pillars of success

10.1   What would you consider to be your pillars of success so far ?

10.2   Who is the most influential person in the group ?

10.3   What contribution does this person have towards the success of the group ?

10.4   How critical is the following to your success so far:

▸   Your organisational strength,

▸   Funding and

▸   Supervision by the extension officer ?

APPENDIX H

Willowfontein

Input data of the simulated observed scenario

BLOCK I: ATMOSPHERIC INFORMATION

MaxAL					(MaxAL = number of atmospheric data records)		
63							
hCritS					(max. allowed pressure head at the soil surface)		
1E+30							
tAtm	Prec.		rSoil	rRoot	hCritA	rt	ht
0		0	0.00029	0.00029	100000	0	-44.1
12		0	0.00029	0.00029	100000	0	-44.2
24		0	0.00029	0.00029	100000	0	-44.3
36		0	0.00029	0.00029	100000	0	-44.4
48		0	0.00029	0.00029	100000	0	-44.5
60		0	0.00029	0.00029	100000	0	-44.6
1000		0	0.00029	0.00029	100000	0	-44.7
2778		0	0.00029	0.00029	100000	0	-44.8
2808		0	0.00029	0.00029	100000	0	-44.9
2838		0	0.00029	0.00029	100000	0	0
3000		0	0.00029	0.00029	100000	0	-40
5000		0	0.00029	0.00029	100000	0	-46.8
8588		0	0.00029	0.00029	100000	0	-46.8
8618		0	0.00029	0.00029	100000	0	0
8900		0	0.00029	0.00029	100000	0	-40
13584		0	0.00029	0.00029	100000	0	-46.5
13596		0	0.00029	0.00029	100000	0	-46.5
13608		0	0.00029	0.00029	100000	0	-46.5
13620		0	0.00029	0.00029	100000	0	-46.5
13632		0	0.00029	0.00029	100000	0	-46.5
13644		0	0.00029	0.00029	100000	0	-46.6
13656		0	0.00029	0.00029	100000	0	-46.7
13668		0	0.00029	0.00029	100000	0	-46.8
13680		0	0.00029	0.00029	100000	0	-46.9
13692		0	0.00029	0.00029	100000	0	-46.9
14262		0	0.00029	0.00029	100000	0	-47.5
14832		0	0.00029	0.00029	100000	0	-47.5
14862		0	0.00029	0.00029	100000	0	0
15000		0	0.00029	0.00029	100000	0	-33
15005		0	0.00029	0.00029	100000	0	-33.5
15012		0	0.00029	0.00029	100000	0	-34
15024		0	0.00029	0.00029	100000	0	-34.5
15036		0	0.00029	0.00029	100000	0	-35
15048		0	0.00029	0.00029	100000	0	-35.5
15060		0	0.00029	0.00029	100000	0	-36
15072		0	0.00029	0.00029	100000	0	-36.5
15084		0	0.00029	0.00029	100000	0	-37
15096		0	0.00029	0.00029	100000	0	-37.5
15108		0	0.00029	0.00029	100000	0	-38
15120		0	0.00029	0.00029	100000	0	-38.5
16476		0	0.00029	0.00029	100000	0	-39
16488		0	0.00029	0.00029	100000	0	-39.5
16500		0	0.00029	0.00029	100000	0	-40
16512		0	0.00029	0.00029	100000	0	-41.5
16524		0	0.00029	0.00029	100000	0	-42
16536		0	0.00029	0.00029	100000	0	-42.5
16548		0	0.00029	0.00029	100000	0	-43
16560		0	0.00029	0.00029	100000	0	-43.5
17940		0	0.00029	0.00029	100000	0	-44
17952		0	0.00029	0.00029	100000	0	-44.5
17964		0	0.00029	0.00029	100000	0	-45
End							

Input data of the simulated efficient scenario

BLOCK I: ATMOSPHERIC INFORMATION

MaxAL				(MaxAL = number of atmospheric data records)		
63						
hCritS				(max. allowed pressure head at the soil surface)		
1E+30						
tAtm	Prec.	rSoil	rRoot	hCritA	rt	ht
0	0	0.00029	0.00029	100000	0	-44.1
12	0	0.00029	0.00029	100000	0	-44.2
24	0	0.00029	0.00029	100000	0	-44.3
36	0	0.00029	0.00029	100000	0	-44.4
48	0	0.00029	0.00029	100000	0	-44.5
60	0	0.00029	0.00029	100000	0	-44.6
1000	0	0.00029	0.00029	100000	0	-44.7
2778	0	0.00029	0.00029	100000	0	-44.8
2808	0	0.00029	0.00029	100000	0	-44.9
2823	0	0.00029	0.00029	100000	0	-15
3000	0	0.00029	0.00029	100000	0	-40
5000	0	0.00029	0.00029	100000	0	-46.8
5653	0	0.00029	0.00029	100000	0	-46.8
5668	0	0.00029	0.00029	100000	0	-10
6000	0	0.00029	0.00029	100000	0	-46.8
7105	0	0.00029	0.00029	100000	0	-46.8
7120	0	0.00029	0.00029	100000	0	-10
7500	0	0.00029	0.00029	100000	0	-46.8
8588	0	0.00029	0.00029	100000	0	-46.8
8603	0	0.00029	0.00029	100000	0	-10
8900	0	0.00029	0.00029	100000	0	-40
9000	0	0.00029	0.00029	100000	0	-46.5
11680	0	0.00029	0.00029	100000	0	-46.5
11695	0	0.00029	0.00029	100000	0	-10
12000	0	0.00029	0.00029	100000	0	-46.5
13241	0	0.00029	0.00029	100000	0	-46.5
13256	0	0.00029	0.00029	100000	0	-10
13584	0	0.00029	0.00029	100000	0	-46.5
13596	0	0.00029	0.00029	100000	0	-46.5
13608	0	0.00029	0.00029	100000	0	-46.5
13620	0	0.00029	0.00029	100000	0	-46.5
13632	0	0.00029	0.00029	100000	0	-46.5
13644	0	0.00029	0.00029	100000	0	-46.6
13656	0	0.00029	0.00029	100000	0	-46.7
13668	0	0.00029	0.00029	100000	0	-46.8
13680	0	0.00029	0.00029	100000	0	-46.9
13692	0	0.00029	0.00029	100000	0	-46.9
14262	0	0.00029	0.00029	100000	0	-47.5
14832	0	0.00029	0.00029	100000	0	-47.5
14847	0	0.00029	0.00029	100000	0	-10
15000	0	0.00029	0.00029	100000	0	-33
15005	0	0.00029	0.00029	100000	0	-33.5
15012	0	0.00029	0.00029	100000	0	-34
15024	0	0.00029	0.00029	100000	0	-34.5
15036	0	0.00029	0.00029	100000	0	-35
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.		.	.		.	.
16560	0	0.00029	0.00029	100000	0	-43.5
17940	0	0.00029	0.00029	100000	0	-44
17952	0	0.00029	0.00029	100000	0	-44.5
17964	0	0.00029	0.00029	100000	0	-45
End						

APPENDIX I

Taylors Halt

Input data of the simulated observed scenario

BLOCK I: ATMOSPHERIC INFORMATION

MaxAL				(MaxAL = number of atmospheric data records)		
399						
hCritS				(max. allowed pressure head at the soil surface)		
1E+30						

tAtm	Prec	rSoil	rRoot	hCritA	rt	ht
0	0	0.00029	0.00029	100000	0	0
1440	0.0019	0.00029	0.00029	100000	0	0
1480	0.00139	0.00029	0.00029	100000	0	0
1568	0.00112	0.00029	0.00029	100000	0	0
1666	0.00109	0.00029	0.00029	100000	0	0
1719	0.00127	0.00029	0.00029	100000	0	0
1803	0.00113	0.00029	0.00029	100000	0	0
2696	0.00091	0.00029	0.00029	100000	0	0
2721	0.00169	0.00029	0.00029	100000	0	0
2750	0.00158	0.00029	0.00029	100000	0	0
2880	0.00089	0.00029	0.00029	100000	0	0
2910	0.00156	0.00029	0.00029	100000	0	0
3711	0.00091	0.00029	0.00029	100000	0	0
4320	0.00089	0.00029	0.00029	100000	0	0
5760	0.00089	0.00029	0.00029	100000	0	0
7200	0.00089	0.00029	0.00029	100000	0	0
8640	0.00089	0.00029	0.00029	100000	0	0
10080	0.00089	0.00029	0.00029	100000	0	0
11520	0.00089	0.00029	0.00029	100000	0	0
12677	0.00091	0.00029	0.00029	100000	0	0
12687	0.00289	0.00029	0.00029	100000	0	0
12689	0.01089	0.00029	0.00029	100000	0	0
12690	0.02089	0.00029	0.00029	100000	0	0
12693	0.00756	0.00029	0.00029	100000	0	0
12697	0.00589	0.00029	0.00029	100000	0	0
12698	0.02089	0.00029	0.00029	100000	0	0
12706	0.00339	0.00029	0.00029	100000	0	0
12723	0.00207	0.00029	0.00029	100000	0	0
12739	0.00214	0.00029	0.00029	100000	0	0
12742	0.00756	0.00029	0.00029	100000	0	0
12746	0.00589	0.00029	0.00029	100000	0	0
12751	0.00489	0.00029	0.00029	100000	0	0
12754	0.00756	0.00029	0.00029	100000	0	0
12755	0.02089	0.00029	0.00029	100000	0	0
12756	0.02089	0.00029	0.00029	100000	0	0
12757	0.02089	0.00029	0.00029	100000	0	0
12759	0.01089	0.00029	0.00029	100000	0	0
12764	0.00489	0.00029	0.00029	100000	0	0
12777	0.00243	0.00029	0.00029	100000	0	0
12785	0.00339	0.00029	0.00029	100000	0	0
12793	0.00339	0.00029	0.00029	100000	0	0
12800	0.00375	0.00029	0.00029	100000	0	0
12960	0.00089	0.00029	0.00029	100000	0	0
14400	0.00089	0.00029	0.00029	100000	0	0
15840	0.00089	0.00029	0.00029	100000	0	0
16982	0.00091	0.00029	0.00029	100000	0	0
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41760	0.0012	0.00029	0.00029	100000	0	0
43200	0.0012	0.00029	0.00029	100000	0	0
44640	0.0012	0.00029	0.00029	100000	0	0
End						

Input data of the simulated efficient scenario

tAtm	Prec	rSoil	rRoot	hCritA	rt	ht
0	0.00000	0.00029	0.00029	100000	0	0
1440	0.00162	0.00029	0.00029	100000	0	0
1480	0.00118	0.00029	0.00029	100000	0	0
1568	0.00095	0.00029	0.00029	100000	0	0
1666	0.00093	0.00029	0.00029	100000	0	0
1719	0.00108	0.00029	0.00029	100000	0	0
1803	0.00096	0.00029	0.00029	100000	0	0
2696	0.00077	0.00029	0.00029	100000	0	0
2721	0.00144	0.00029	0.00029	100000	0	0
2750	0.00134	0.00029	0.00029	100000	0	0
2880	0.00076	0.00029	0.00029	100000	0	0
2910	0.00133	0.00029	0.00029	100000	0	0
3711	0.00077	0.00029	0.00029	100000	0	0
4320	0.00076	0.00029	0.00029	100000	0	0
5760	0.00076	0.00029	0.00029	100000	0	0
7200	0.00076	0.00029	0.00029	100000	0	0
8640	0.00076	0.00029	0.00029	100000	0	0
10080	0.00076	0.00029	0.00029	100000	0	0
11520	0.00076	0.00029	0.00029	100000	0	0
12677	0.00077	0.00029	0.00029	100000	0	0
12687	0.00246	0.00029	0.00029	100000	0	0
12689	0.00926	0.00029	0.00029	100000	0	0
12690	0.01776	0.00029	0.00029	100000	0	0
12693	0.00643	0.00029	0.00029	100000	0	0
12697	0.00501	0.00029	0.00029	100000	0	0
12698	0.01776	0.00029	0.00029	100000	0	0
12706	0.00288	0.00029	0.00029	100000	0	0
12723	0.00176	0.00029	0.00029	100000	0	0
12739	0.00182	0.00029	0.00029	100000	0	0
12742	0.00643	0.00029	0.00029	100000	0	0
12746	0.00501	0.00029	0.00029	100000	0	0
12751	0.00416	0.00029	0.00029	100000	0	0
12754	0.00643	0.00029	0.00029	100000	0	0
12755	0.01776	0.00029	0.00029	100000	0	0
12756	0.01776	0.00029	0.00029	100000	0	0
12757	0.01776	0.00029	0.00029	100000	0	0
12759	0.00926	0.00029	0.00029	100000	0	0
12764	0.00416	0.00029	0.00029	100000	0	0
12777	0.00207	0.00029	0.00029	100000	0	0
12785	0.00288	0.00029	0.00029	100000	0	0
12793	0.00288	0.00029	0.00029	100000	0	0
12800	0.00319	0.00029	0.00029	100000	0	0
12960	0.00076	0.00029	0.00029	100000	0	0
14400	0.00076	0.00029	0.00029	100000	0	0
15840	0.00076	0.00029	0.00029	100000	0	0
16982	0.00077	0.00029	0.00029	100000	0	0
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41760	0.00102	0.00029	0.00029	100000	0	0
43200	0.00102	0.00029	0.00029	100000	0	0
44640	0.00102	0.00029	0.00029	100000	0	0
End						

APPENDIX J

Willowfontein

Output results of the simulated observed scenario

time	Node (185) 0.72 cm			Node (187) 0.37 cm			Node (433) 0.19 cm		
	hw	theta	conc.	hw	theta	conc.	hw	theta	conc.
0.000	-119.998	0.3212	0.000E+00	-117.363	0.3220	0.000E+00	-50.223	0.3932	0.000E+00
0.001	-119.998	0.3212	0.000E+00	-117.362	0.3220	0.000E+00	-50.223	0.3932	0.000E+00
0.002	-119.998	0.3212	0.000E+00	-117.359	0.3220	0.000E+00	-50.223	0.3932	0.000E+00
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.	.	.	.	.	.	.	.	.	.
112.208	-119.722	0.3213	0.000E+00	-83.880	0.3342	0.000E+00	-71.496	0.3750	0.000E+00
124.890	-119.683	0.3213	0.000E+00	-83.849	0.3342	0.000E+00	-72.903	0.3740	0.000E+00
137.573	-119.640	0.3213	0.000E+00	-83.880	0.3342	0.000E+00	-74.231	0.3731	0.000E+00
150.256	-119.594	0.3214	0.000E+00	-83.954	0.3341	0.000E+00	-75.507	0.3722	0.000E+00
162.939	-119.544	0.3214	0.000E+00	-84.044	0.3341	0.000E+00	-77.045	0.3714	0.000E+00
175.621	-119.489	0.3214	0.000E+00	-84.138	0.3340	0.000E+00	-78.457	0.3707	0.000E+00
188.304	-119.430	0.3214	0.000E+00	-84.234	0.3340	0.000E+00	-79.753	0.3700	0.000E+00
200.987	-119.366	0.3214	0.000E+00	-84.335	0.3340	0.000E+00	-80.968	0.3694	0.000E+00
213.670	-119.295	0.3214	0.000E+00	-84.441	0.3339	0.000E+00	-82.119	0.3688	0.000E+00
230.051	-119.198	0.3215	0.000E+00	-84.583	0.3338	0.000E+00	-83.509	0.3681	0.000E+00
246.433	-119.086	0.3215	0.000E+00	-84.737	0.3338	0.000E+00	-84.843	0.3675	0.000E+00
262.815	-118.962	0.3216	0.000E+00	-84.900	0.3337	0.000E+00	-86.114	0.3668	0.000E+00
279.197	-118.825	0.3216	0.000E+00	-85.066	0.3336	0.000E+00	-87.332	0.3662	0.000E+00
295.579	-118.674	0.3216	0.000E+00	-85.231	0.3335	0.000E+00	-88.503	0.3657	0.000E+00
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8752.256	-22.412	0.4040	0.000E+00	-37.526	0.3748	0.000E+00	-43.869	0.4010	0.000E+00
8759.643	-22.476	0.4038	0.000E+00	-38.093	0.3740	0.000E+00	-44.544	0.4001	0.000E+00
8767.030	-22.542	0.4037	0.000E+00	-38.627	0.3733	0.000E+00	-45.187	0.3992	0.000E+00
8774.418	-22.610	0.4035	0.000E+00	-39.123	0.3726	0.000E+00	-45.798	0.3983	0.000E+00
8784.078	-22.701	0.4033	0.000E+00	-39.723	0.3718	0.000E+00	-46.550	0.3973	0.000E+00
8793.738	-22.795	0.4031	0.000E+00	-40.284	0.3711	0.000E+00	-47.266	0.3963	0.000E+00
8803.398	-22.891	0.4029	0.000E+00	-40.809	0.3703	0.000E+00	-48.028	0.3954	0.000E+00
8813.059	-22.988	0.4027	0.000E+00	-41.300	0.3697	0.000E+00	-48.761	0.3947	0.000E+00
8825.479	-23.114	0.4024	0.000E+00	-41.898	0.3689	0.000E+00	-49.621	0.3938	0.000E+00
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13038.930	-46.847	0.3621	0.000E+00	-85.679	0.3333	0.000E+00	-162.263	0.3449	0.000E+00
13116.800	-47.040	0.3619	0.000E+00	-86.022	0.3332	0.000E+00	-163.490	0.3448	0.000E+00
13210.240	-47.266	0.3616	0.000E+00	-86.415	0.3330	0.000E+00	-164.874	0.3445	0.000E+00
13303.680	-47.486	0.3613	0.000E+00	-86.795	0.3328	0.000E+00	-166.271	0.3443	0.000E+00
13397.120	-47.729	0.3610	0.000E+00	-87.160	0.3326	0.000E+00	-167.623	0.3441	0.000E+00
13490.560	-47.956	0.3608	0.000E+00	-87.512	0.3325	0.000E+00	-168.961	0.3439	0.000E+00
13584.000	-48.170	0.3606	0.000E+00	-87.854	0.3323	0.000E+00	-170.296	0.3437	0.000E+00
13596.000	-48.197	0.3606	0.000E+00	-87.900	0.3323	0.000E+00	-170.472	0.3437	0.000E+00
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17516.890	-36.135	0.3773	0.000E+00	-65.301	0.3452	0.000E+00	-90.172	0.3648	0.000E+00
17563.910	-36.325	0.3769	0.000E+00	-65.557	0.3450	0.000E+00	-90.714	0.3645	0.000E+00
17610.920	-36.517	0.3766	0.000E+00	-65.820	0.3448	0.000E+00	-91.271	0.3643	0.000E+00
17676.730	-36.789	0.3761	0.000E+00	-66.180	0.3446	0.000E+00	-92.023	0.3639	0.000E+00
17742.550	-37.057	0.3757	0.000E+00	-66.531	0.3443	0.000E+00	-92.765	0.3635	0.000E+00
17808.370	-37.317	0.3752	0.000E+00	-66.870	0.3441	0.000E+00	-93.485	0.3632	0.000E+00
17874.180	-37.578	0.3748	0.000E+00	-67.204	0.3439	0.000E+00	-94.196	0.3628	0.000E+00
17940.000	-37.856	0.3744	0.000E+00	-67.530	0.3436	0.000E+00	-94.899	0.3625	0.000E+00
17940.000	-37.856	0.3744	0.000E+00	-67.532	0.3436	0.000E+00	-94.908	0.3625	0.000E+00
17952.000	-37.908	0.3743	0.000E+00	-67.590	0.3436	0.000E+00	-95.039	0.3624	0.000E+00
17952.000	-37.907	0.3743	0.000E+00	-67.590	0.3436	0.000E+00	-95.033	0.3624	0.000E+00
17964.000	-37.959	0.3742	0.000E+00	-67.653	0.3436	0.000E+00	-95.210	0.3623	0.000E+00

Willowfontein

Output results of the simulated efficient scenario

time	Node (185) 0.72 cm			Node (187) 0.37 cm			Node (433) 0.19 cm		
	hw	theta	conc.	hw	theta	conc.	hw	theta	conc.
0.000	-119.998	0.3212	0.000E+00	-117.271	0.3221	0.000E+00	-50.218	0.3932	0.000E+00
0.001	-119.998	0.3212	0.000E+00	-117.271	0.3221	0.000E+00	-50.218	0.3932	0.000E+00
0.002	-119.998	0.3212	0.000E+00	-117.267	0.3221	0.000E+00	-50.218	0.3932	0.000E+00
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
112.208	-119.715	0.3213	0.000E+00	-81.897	0.3351	0.000E+00	-70.470	0.3758	0.000E+00
124.890	-119.672	0.3213	0.000E+00	-81.847	0.3351	0.000E+00	-71.852	0.3748	0.000E+00
137.573	-119.625	0.3213	0.000E+00	-81.856	0.3351	0.000E+00	-73.154	0.3738	0.000E+00
150.256	-119.573	0.3214	0.000E+00	-81.908	0.3351	0.000E+00	-74.391	0.3730	0.000E+00
162.939	-119.517	0.3214	0.000E+00	-82.000	0.3350	0.000E+00	-75.576	0.3721	0.000E+00
175.621	-119.456	0.3214	0.000E+00	-82.111	0.3350	0.000E+00	-77.027	0.3714	0.000E+00
188.304	-119.389	0.3214	0.000E+00	-82.231	0.3349	0.000E+00	-78.349	0.3707	0.000E+00
200.987	-119.316	0.3214	0.000E+00	-82.355	0.3349	0.000E+00	-79.579	0.3701	0.000E+00
213.670	-119.235	0.3215	0.000E+00	-82.489	0.3348	0.000E+00	-80.727	0.3695	0.000E+00
230.051	-119.123	0.3215	0.000E+00	-82.673	0.3347	0.000E+00	-82.091	0.3688	0.000E+00
246.433	-118.994	0.3215	0.000E+00	-82.874	0.3346	0.000E+00	-83.410	0.3682	0.000E+00
262.815	-118.851	0.3216	0.000E+00	-83.081	0.3345	0.000E+00	-84.670	0.3676	0.000E+00
279.197	-118.692	0.3216	0.000E+00	-83.288	0.3344	0.000E+00	-85.878	0.3670	0.000E+00
295.579	-118.517	0.3217	0.000E+00	-83.489	0.3343	0.000E+00	-87.040	0.3664	0.000E+00
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8757.440	-50.399	0.3584	0.000E+00	-66.851	0.3441	0.000E+00	-75.577	0.3721	0.000E+00
8793.080	-49.939	0.3588	0.000E+00	-66.526	0.3443	0.000E+00	-77.517	0.3711	0.000E+00
8828.720	-49.489	0.3593	0.000E+00	-66.593	0.3443	0.000E+00	-79.284	0.3702	0.000E+00
8864.359	-49.067	0.3597	0.000E+00	-66.834	0.3441	0.000E+00	-80.728	0.3695	0.000E+00
8900.000	-48.681	0.3601	0.000E+00	-67.152	0.3439	0.000E+00	-81.931	0.3689	0.000E+00
8900.001	-48.681	0.3601	0.000E+00	-67.154	0.3439	0.000E+00	-81.934	0.3689	0.000E+00
8950.000	-48.227	0.3605	0.000E+00	-68.059	0.3433	0.000E+00	-85.388	0.3672	0.000E+00
8975.000	-48.023	0.3607	0.000E+00	-68.604	0.3429	0.000E+00	-87.386	0.3662	0.000E+00
9000.000	-47.842	0.3609	0.000E+00	-69.217	0.3425	0.000E+00	-89.535	0.3651	0.000E+00
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13042.440	-49.295	0.3595	0.000E+00	-87.704	0.3324	0.000E+00	-166.857	0.3442	0.000E+00
13108.630	-49.419	0.3594	0.000E+00	-88.154	0.3322	0.000E+00	-168.926	0.3439	0.000E+00
13174.810	-49.545	0.3592	0.000E+00	-88.572	0.3320	0.000E+00	-170.906	0.3436	0.000E+00
13241.000	-49.670	0.3591	0.000E+00	-88.962	0.3318	0.000E+00	-172.769	0.3433	0.000E+00
13241.000	-49.669	0.3591	0.000E+00	-88.965	0.3318	0.000E+00	-172.700	0.3433	0.000E+00
13256.000	-49.686	0.3591	0.000E+00	-82.960	0.3346	0.000E+00	-92.462	0.3637	0.000E+00
13256.000	-49.686	0.3591	0.000E+00	-82.959	0.3346	0.000E+00	-92.487	0.3637	0.000E+00
13310.670	-49.433	0.3593	0.000E+00	-71.279	0.3410	0.000E+00	-75.250	0.3723	0.000E+00
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17388.330	-41.562	0.3693	0.000E+00	-71.327	0.3410	0.000E+00	-101.915	0.3600	0.000E+00
17449.630	-41.699	0.3691	0.000E+00	-71.598	0.3408	0.000E+00	-102.613	0.3598	0.000E+00
17531.350	-41.878	0.3689	0.000E+00	-71.941	0.3406	0.000E+00	-103.485	0.3595	0.000E+00
17613.080	-42.052	0.3687	0.000E+00	-72.276	0.3403	0.000E+00	-104.339	0.3592	0.000E+00
17694.810	-42.222	0.3684	0.000E+00	-72.591	0.3401	0.000E+00	-105.141	0.3589	0.000E+00
17776.540	-42.387	0.3682	0.000E+00	-72.889	0.3399	0.000E+00	-105.896	0.3586	0.000E+00
17858.270	-42.547	0.3680	0.000E+00	-73.175	0.3397	0.000E+00	-106.662	0.3584	0.000E+00
17940.000	-42.703	0.3678	0.000E+00	-73.448	0.3395	0.000E+00	-107.389	0.3581	0.000E+00
17940.000	-42.703	0.3678	0.000E+00	-73.450	0.3395	0.000E+00	-107.395	0.3581	0.000E+00
17952.000	-42.726	0.3677	0.000E+00	-73.489	0.3395	0.000E+00	-107.511	0.3581	0.000E+00
17952.000	-42.726	0.3677	0.000E+00	-73.488	0.3395	0.000E+00	-107.506	0.3581	0.000E+00
17964.000	-42.749	0.3677	0.000E+00	-73.532	0.3395	0.000E+00	-107.667	0.3580	0.000E+00

APPENDIX K

Taylors Halt

Output results of the simulated observed scenario

	Node (154)	0.72 cm			Node (462)	0.47 cm			Node (469)	0.20 cm	
time	hw	theta	conc.	hw	theta	conc.	hw	theta	conc.
0.000	-99.962	0.4497	0.000E+00	-100.194	0.4794	0.000E+00	-100.178	0.4794	0.000E+00
0.001	-99.965	0.4497	0.000E+00	-100.179	0.4794	0.000E+00	-100.164	0.4794	0.000E+00
0.002	-99.963	0.4497	0.000E+00	-100.193	0.4794	0.000E+00	-100.177	0.4794	0.000E+00
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8880.000	-77.472	0.4706	0.000E+00	-154.143	0.4458	0.000E+00	-178.964	0.4358	0.000E+00
9120.000	-77.700	0.4704	0.000E+00	-154.648	0.4456	0.000E+00	-179.666	0.4355	0.000E+00
9360.000	-77.921	0.4702	0.000E+00	-155.128	0.4454	0.000E+00	-180.331	0.4352	0.000E+00
9600.000	-78.134	0.4699	0.000E+00	-155.586	0.4452	0.000E+00	-180.963	0.4349	0.000E+00
9840.000	-78.340	0.4697	0.000E+00	-156.024	0.4451	0.000E+00	-181.564	0.4347	0.000E+00
10080.000	-78.541	0.4696	0.000E+00	-156.443	0.4449	0.000E+00	-182.140	0.4345	0.000E+00
10368.000	-78.771	0.4693	0.000E+00	-156.919	0.4447	0.000E+00	-182.785	0.4342	0.000E+00
10656.000	-78.991	0.4691	0.000E+00	-157.381	0.4445	0.000E+00	-183.412	0.4340	0.000E+00
10944.000	-79.202	0.4689	0.000E+00	-157.819	0.4443	0.000E+00	-184.007	0.4337	0.000E+00
11232.000	-79.405	0.4687	0.000E+00	-158.237	0.4442	0.000E+00	-184.574	0.4335	0.000E+00
11520.000	-79.600	0.4685	0.000E+00	-158.637	0.4440	0.000E+00	-185.116	0.4333	0.000E+00
11520.000	-79.600	0.4685	0.000E+00	-158.637	0.4440	0.000E+00	-185.118	0.4333	0.000E+00
11680.000	-79.705	0.4684	0.000E+00	-158.829	0.4439	0.000E+00	-185.323	0.4332	0.000E+00
11770.000	-79.763	0.4684	0.000E+00	-158.922	0.4439	0.000E+00	-185.408	0.4331	0.000E+00
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17878.750	-67.873	0.4818	0.000E+00	-97.452	0.4815	0.000E+00	-96.164	0.4824	0.000E+00
18058.380	-65.789	0.4843	0.000E+00	-100.357	0.4793	0.000E+00	-101.649	0.4783	0.000E+00
18238.000	-64.252	0.4862	0.000E+00	-103.127	0.4772	0.000E+00	-106.386	0.4748	0.000E+00
18238.000	-64.252	0.4862	0.000E+00	-103.127	0.4772	0.000E+00	-106.387	0.4748	0.000E+00
18241.000	-64.227	0.4862	0.000E+00	-103.173	0.4772	0.000E+00	-106.463	0.4747	0.000E+00
18241.000	-64.226	0.4862	0.000E+00	-103.173	0.4772	0.000E+00	-106.463	0.4747	0.000E+00
18276.000	-63.950	0.4866	0.000E+00	-103.667	0.4768	0.000E+00	-107.166	0.4742	0.000E+00
18276.000	-63.950	0.4866	0.000E+00	-103.664	0.4768	0.000E+00	-107.168	0.4742	0.000E+00
18511.000	-62.802	0.4880	0.000E+00	-106.210	0.4749	0.000E+00	-110.945	0.4713	0.000E+00
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26736.670	-56.324	0.4968	0.000E+00	-104.561	0.4761	0.000E+00	-110.093	0.4720	0.000E+00
26814.590	-56.393	0.4967	0.000E+00	-104.819	0.4760	0.000E+00	-110.458	0.4717	0.000E+00
26923.670	-56.493	0.4966	0.000E+00	-105.177	0.4757	0.000E+00	-110.955	0.4714	0.000E+00
27069.110	-56.632	0.4963	0.000E+00	-105.639	0.4753	0.000E+00	-111.582	0.4709	0.000E+00
27214.550	-56.777	0.4961	0.000E+00	-106.081	0.4750	0.000E+00	-112.161	0.4705	0.000E+00
27360.000	-56.925	0.4959	0.000E+00	-106.501	0.4747	0.000E+00	-112.696	0.4701	0.000E+00
27600.000	-57.175	0.4955	0.000E+00	-107.138	0.4742	0.000E+00	-113.479	0.4695	0.000E+00
27840.000	-57.427	0.4952	0.000E+00	-107.720	0.4738	0.000E+00	-114.181	0.4689	0.000E+00
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41468.660	-56.081	0.4972	0.000E+00	-105.698	0.4753	0.000E+00	-111.869	0.4707	0.000E+00
41760.000	-56.462	0.4966	0.000E+00	-106.474	0.4747	0.000E+00	-112.817	0.4699	0.000E+00
42000.000	-56.768	0.4961	0.000E+00	-107.068	0.4743	0.000E+00	-113.523	0.4694	0.000E+00
42300.000	-57.140	0.4956	0.000E+00	-107.740	0.4738	0.000E+00	-114.306	0.4688	0.000E+00
42600.000	-57.492	0.4951	0.000E+00	-108.358	0.4733	0.000E+00	-115.017	0.4683	0.000E+00
42900.000	-57.826	0.4946	0.000E+00	-108.919	0.4729	0.000E+00	-115.657	0.4678	0.000E+00
43200.000	-58.142	0.4941	0.000E+00	-109.433	0.4725	0.000E+00	-116.239	0.4674	0.000E+00
43488.000	-58.434	0.4937	0.000E+00	-109.886	0.4722	0.000E+00	-116.748	0.4670	0.000E+00
43776.000	-58.714	0.4933	0.000E+00	-110.295	0.4718	0.000E+00	-117.198	0.4667	0.000E+00
44064.000	-58.979	0.4929	0.000E+00	-110.673	0.4716	0.000E+00	-117.611	0.4664	0.000E+00
44352.000	-59.230	0.4925	0.000E+00	-111.024	0.4713	0.000E+00	-117.990	0.4661	0.000E+00
44640.000	-59.465	0.4921	0.000E+00	-111.348	0.4711	0.000E+00	-118.339	0.4658	0.000E+00

Taylors Halt

Output results of the simulated efficient scenario

time	Node (154) 0.72 cm			Node (462) 0.47 cm			Node (469) 0.20 cm		
	hw	theta	conc.	hw	theta	conc.	hw	theta	conc.
0.000	-99.962	0.4497	0.000E+00	-100.194	0.4794	0.000E+00	-100.178	0.4794	0.000E+00
0.001	-99.965	0.4497	0.000E+00	-100.179	0.4794	0.000E+00	-100.164	0.4794	0.000E+00
0.002	-99.963	0.4497	0.000E+00	-100.193	0.4794	0.000E+00	-100.177	0.4794	0.000E+00
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8880.000	-81.027	0.4671	0.000E+00	-166.720	0.4407	0.000E+00	-199.415	0.4283	0.000E+00
9120.000	-81.373	0.4668	0.000E+00	-167.536	0.4404	0.000E+00	-200.583	0.4280	0.000E+00
9360.000	-81.709	0.4665	0.000E+00	-168.309	0.4401	0.000E+00	-201.698	0.4276	0.000E+00
9600.000	-82.036	0.4662	0.000E+00	-169.051	0.4398	0.000E+00	-202.769	0.4273	0.000E+00
9840.000	-82.354	0.4658	0.000E+00	-169.764	0.4395	0.000E+00	-203.801	0.4270	0.000E+00
10080.000	-82.663	0.4655	0.000E+00	-170.453	0.4392	0.000E+00	-204.798	0.4267	0.000E+00
10320.000	-82.962	0.4653	0.000E+00	-171.119	0.4389	0.000E+00	-205.763	0.4264	0.000E+00
10560.000	-83.253	0.4650	0.000E+00	-171.763	0.4387	0.000E+00	-206.698	0.4262	0.000E+00
10800.000	-83.534	0.4647	0.000E+00	-172.386	0.4384	0.000E+00	-207.604	0.4259	0.000E+00
11040.000	-83.808	0.4644	0.000E+00	-172.998	0.4382	0.000E+00	-208.500	0.4256	0.000E+00
11280.000	-84.073	0.4642	0.000E+00	-173.594	0.4379	0.000E+00	-209.370	0.4254	0.000E+00
11520.000	-84.331	0.4639	0.000E+00	-174.173	0.4377	0.000E+00	-210.211	0.4251	0.000E+00
11520.000	-84.331	0.4639	0.000E+00	-174.173	0.4377	0.000E+00	-210.209	0.4251	0.000E+00
11680.000	-84.498	0.4638	0.000E+00	-174.530	0.4376	0.000E+00	-210.682	0.4250	0.000E+00
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17854.800	-74.668	0.4736	0.000E+00	-105.261	0.4756	0.000E+00	-104.051	0.4765	0.000E+00
17982.530	-72.982	0.4756	0.000E+00	-107.273	0.4741	0.000E+00	-108.202	0.4734	0.000E+00
18110.270	-71.484	0.4774	0.000E+00	-109.344	0.4726	0.000E+00	-112.148	0.4705	0.000E+00
18238.000	-70.229	0.4789	0.000E+00	-111.367	0.4710	0.000E+00	-115.799	0.4677	0.000E+00
18238.000	-70.228	0.4789	0.000E+00	-111.361	0.4710	0.000E+00	-115.794	0.4677	0.000E+00
18241.000	-70.200	0.4790	0.000E+00	-111.414	0.4710	0.000E+00	-115.883	0.4676	0.000E+00
18241.000	-70.200	0.4790	0.000E+00	-111.414	0.4710	0.000E+00	-115.884	0.4676	0.000E+00
18276.000	-69.881	0.4794	0.000E+00	-111.934	0.4706	0.000E+00	-116.687	0.4670	0.000E+00
18276.000	-69.881	0.4794	0.000E+00	-111.931	0.4706	0.000E+00	-116.686	0.4670	0.000E+00
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26768.000	-58.777	0.4932	0.000E+00	-107.691	0.4738	0.000E+00	-113.418	0.4695	0.000E+00
27064.000	-58.854	0.4931	0.000E+00	-108.399	0.4733	0.000E+00	-114.435	0.4687	0.000E+00
27360.000	-58.972	0.4929	0.000E+00	-109.058	0.4728	0.000E+00	-115.342	0.4681	0.000E+00
27648.000	-59.114	0.4927	0.000E+00	-109.640	0.4723	0.000E+00	-116.115	0.4675	0.000E+00
27936.000	-59.272	0.4924	0.000E+00	-110.152	0.4719	0.000E+00	-116.773	0.4670	0.000E+00
28224.000	-59.440	0.4922	0.000E+00	-110.603	0.4716	0.000E+00	-117.333	0.4666	0.000E+00
28512.000	-59.611	0.4919	0.000E+00	-111.005	0.4713	0.000E+00	-117.820	0.4662	0.000E+00
28800.000	-59.782	0.4917	0.000E+00	-111.364	0.4710	0.000E+00	-118.244	0.4659	0.000E+00
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41468.660	-56.088	0.4972	0.000E+00	-105.708	0.4753	0.000E+00	-111.880	0.4707	0.000E+00
41760.000	-56.468	0.4966	0.000E+00	-106.483	0.4747	0.000E+00	-112.827	0.4699	0.000E+00
42000.000	-56.775	0.4961	0.000E+00	-107.077	0.4743	0.000E+00	-113.533	0.4694	0.000E+00
42300.000	-57.146	0.4956	0.000E+00	-107.749	0.4737	0.000E+00	-114.315	0.4688	0.000E+00
42600.000	-57.497	0.4951	0.000E+00	-108.365	0.4733	0.000E+00	-115.025	0.4683	0.000E+00
42900.000	-57.831	0.4946	0.000E+00	-108.926	0.4729	0.000E+00	-115.664	0.4678	0.000E+00
43200.000	-58.147	0.4941	0.000E+00	-109.440	0.4725	0.000E+00	-116.246	0.4674	0.000E+00
43488.000	-58.438	0.4937	0.000E+00	-109.892	0.4722	0.000E+00	-116.754	0.4670	0.000E+00
43776.000	-58.718	0.4933	0.000E+00	-110.301	0.4718	0.000E+00	-117.204	0.4667	0.000E+00
44064.000	-58.983	0.4929	0.000E+00	-110.679	0.4716	0.000E+00	-117.616	0.4664	0.000E+00
44352.000	-59.234	0.4925	0.000E+00	-111.029	0.4713	0.000E+00	-117.995	0.4661	0.000E+00
44640.000	-59.469	0.4921	0.000E+00	-111.352	0.4711	0.000E+00	-118.344	0.4658	0.000E+00