REGULATED DEFICIT IRRIGATION AS A WATER MANAGEMENT STRATEGY IN BEAN PRODUCTION: A CASE STUDY OF THE USANGU PLAINS IN TANZANIA

BY

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ABSTRACT

This study was conducted at Herman canal irrigation scheme in Tanzania to evaluate the efficacy of Regulated Deficit Irrigation (RDI) as a water management strategy for field crops in smallholder irrigation schemes under semi-arid conditions. There were five irrigation treatments in a randomised complete block design: a farmer irrigated, a control, and three RDI treatments. Water productivity (WP) varied spatially with the lowest WP in the Head block. Among treatments, the highest WP (1.10 kg/m^3 and Tsh 883/m^3) was found in RDI at 50% soil moisture depletion that also saved 10% irrigation water with 3% yield reduction. From the current non-volumetric water pricing system in the scheme, irrigation depths by the farmers produced the lowest WP (0.44 kg/m^3 and Tsh 348/m^3) although profits were highest. However, RDI at 50% soil moisture depletion maximised WP and profits than the farmer-irrigated treatment assuming a volumetric water pricing system. The yield response factor for the whole scheme (λ_y = 0.50) suggests that the bean crop was not very sensitive to RDI. However, the crop was more sensitive to RDI in the Head (λ_y = 1.07) than in the Middle (λ_y = 0.35) and Tail (λ_y = 0.33) blocks. The number of seeds per pod was unaffected by water deficits while both the number of pods per plant and 100 seeds weight were reduced by water deficit. Statistically, higher correlations with grain yield were obtained between 100 seeds weight (r = 0.95) and the number of pods per plant (r = 0.91) as compared to the number of seeds per pod (r = 0.89). WP and profits can increase in the scheme if RDI with moderate deficits could be adopted especially when water is charged on actual applied volume.

DECLARATION

I, LIMBANI MALONI GOMANI, do hereby declare to the Senate of the Sokoine University of Agriculture that this dissertation is my own original work that was not submitted for a higher degree in any other University.

Signature: .....

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DEDICATION

To my mother Rebecca and in memory of my father, the late Maloni Nelson Gomani.

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LIST OF ABBREVIATIONS AND SYMBOLS

D_A	Irrigation application depth
ET_a	Actual evapotranspiration
GVP	Gross value of production
IWMI	Irrigation Water Management Institute
NVP	Net value of production
Q	Discharge
R	Neutron count
RAM	Readily available moisture
RDI	Regulated deficit irrigation
SAS	Statistical Analysis Systems
SGVP	Standardised gross value of production
TAM	Total available moisture
Tsh	Tanzania Shillings
V	Irrigation volume
W	Total irrigation water applied
WAD	Water application duration
WP	Water productivity
WP_{GVP_ETa}	Economic productivity of crop water use
WP_{GVP_IRR}	Economic productivity of irrigation water
WP_{Y_ETa}	Physical productivity of crop water use
WP_{Y_IRR}	Physical productivity of irrigation water
WUE	Water use efficiency

CHAPTER ONE

1.0 INTRODUCTION

1.1 Overview of regulated deficit irrigation

Water is a valuable resource and key input in agricultural production such that its scarcity and misuse poses a serious and growing threat to life and sustainable development (Degirmenci *et al.,* 2003). However, in many countries around the world, irrigation water is being threatened due to a growing scarcity of and competition for water among agricultural, domestic and industrial sectors (Ahmad *et al.*, 2004; George *et al.*, 2000; Kirda, 1999). Of the three major sectors, agriculture remains the largest water user, accounting for more than 70% of water withdrawals worldwide and more than 90% of water withdrawals in low-income developing countries (Brito *et al.*, 2003; Carruthers *et al.*, 1997).

As irrigation is a highly consumptive water user and has the greatest impact on net water resources, the challenge for irrigated agriculture is to produce more food with less water and the worsening situation can only be reverted if water is managed more efficiently and judiciously (Ahmad *et al.*, 2004; Hellman *et al*, 2004; Wample *et al.*, 2002). Therefore, prudent use of irrigation water is an immediate necessity and irrigation-scheduling approaches designed to increase the efficiency and optimise irrigation water use are required (Degirmenci *et al.*, 2003; Kirda, 1999). Consequently, there is a growing interest in Regulated Deficit Irrigation (RDI) in order to conserve water and maintain crop production (Pandey *et al.*, 2000).

Regulated Deficit Irrigation is an irrigation strategy that was developed according to demands of plants for water and photo-assimilates throughout different crop growth stages (Kriedemann and Goodwin, 2004; McCarthy *et al.*, 2002). This irrigation strategy was coined by a team of researchers during the 1970s to describe the application of water deficit strategies based on orchard evapotranspiration relative to water loss from an evaporimeter (Kriedemann and Goodwin, 2004). It was developed for use in high-density orchards (peaches and pears) production and later applied to wine grape production (Goodwin and Boland, 2002).

Regulated Deficit Irrigation is the practice of regulating the application of irrigation water at some level below full crop water use. The rationale is to minimise rather than maximise crop water use to induce an accurately timed, mild water stress response with the ultimate outcome that it limits vegetative growth and enhances crop water use efficiency (Kriedemann and Goodwin, 2004). Since crop responses to irrigation water deficits have demonstrated that the sensitivity of yield to water stress is dependent on the phenological phase in which water stress is applied (Doorenbos and Kassam, 1986), the RDI strategy is based on limiting non-beneficial water losses and applying water so that water stress is controlled and occurs when adverse effects on productivity are minimised (Domingo *et al.*, 1996).

The application of RDI improves water use efficiency due largely to reductions in transpiration as canopy growth is constrained in favour of crop development (Goodwin and Boland, 2002). Transpiration is reduced by purposely limiting the available soil moisture so that the crop is exposed to a certain level of water stress

during a particular growth period. Crop water stress is ideally measured with the most relevant indicators in terms of crop water potential and canopy temperature. However, measurement of crop water stress is complex as it varies during the day and may change very quickly in response to wind, temperature, solar radiation, cloud cover and humidity (Rajab, 2002). As such, soil moisture content and potential that may be inferred from soil moisture depletion or estimates of crop water use based on evaporative conditions are more widely used for practical, convenience and cost saving purposes (Kriedemann and Goodwin, 2004).

Understanding the principles of RDI has improved substantially over the past 20 years such that scheduling has evolved from the initial recommendations based on US Class-A pan evaporation towards measuring both soil moisture and crop responses before making management decisions (Kriedemann and Goodwin, 2004). Although physical measurement of soil moisture content in every field presents practical difficulties, an understanding of the principles of water movement in the soil profile and a continuous evaluation of the storage and balance of soil moisture during RDI scheduling is important for efficient soil and water management (Stricevic and Caki, 1997). It is therefore important to know when and how much to irrigate in order to attain agronomic potential as optimal crop production depends greatly on available soil moisture (Mukherjee and Kottegoda, 1992). Today, many methods and measurements are used to determine soil moisture status and their shortcoming is the assumption of a threshold value of soil moisture depletion in the soil for the onset of significant crop stress.

It is evident that root volume is an important factor in the crop growth response to RDI (Pandey *et al.*, 2000). Some studies have suggested that the success of RDI in controlling vigour and maintaining yield arise from both an adaptation to moderate water stress development in a shallow soil volume and/or restricted wetted root volume (Goodwin and Boland, 2002). The control of vegetative growth and establishment of RDI depends on the interaction between rainfall/evaporation, available soil volume for root exploration and the readily available moisture.

Regulated deficit irrigation has been successfully applied on a number of crops belonging to different taxonomical families and possessing diverse characteristics. For instance, RDI was found to be the irrigation strategy that enabled further expansion of irrigated horticulture by improving the efficiency with which orchard and vineyard irrigators use their entitlements (Wample *et al.*, 2002; Romero *et al.*, 2004; Kriedemann and Goodwin, 2004). Water savings in the range of 6-30% of perennial crop plants have been documented as well as consistent improvement in yields quality without significant yield reductions (Domingo *et al.*, 1996; Kriedemann and Goodwin, 2004; Goldhamer, 2000; Gonzalez and Castel, 2004; Hellman *et al.*, 2004; Romero *et al.*, 2004).

Regulated deficit irrigation scheduling is an ideal water saving technique, one way of maximising water use efficiency for higher yields per unit of irrigation water applied (Kirda, 1999; Pandey *et al.*, 2000). Observations to date indicate that RDI is, arguably, the most economical technique for controlling vegetative vigour and a realistic option for long-term management of perennial crop plants and its application

in various environments has led to better understanding of the process, the benefits and the requirements for its adoption (Goodwin and Boland, 2002). However, not much appears to have been investigated on annual crops under more arid conditions. It was thus the aim of this study to gain more insight into the subject as it relates to commonly grown crops under smallholder and semi-arid conditions. The bean crop was purposely selected and justified for the study since it is one of the commonly grown crops in Tanzania and in the study area in particular.

1.2 Objectives of the Study

1.2.1 Overall objective

The overall objective of the study was to evaluate the efficacy of using RDI as a water management strategy in smallholder irrigation schemes.

1.2.2 Specific objectives

The specific objectives of the study were:

i. To evaluate the performance of RDI in bean production.

ii. To assess the sensitivity of RDI in bean production.

iii. To assess the potential economic benefits of RDI in bean production.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Management of deficit irrigation

Deficit irrigation is basically under-irrigation but useful irrigation management technique for increasing farm income under certain circumstances (English and Nakamura, 1989). It is an irrigation optimising strategy under which crops are deliberately allowed to sustain some degree of water deficit and yield reduction (English, 1990; English and Raja, 1996). Deficit irrigation scheduling may provide an option to increase the effective use of water in sustaining irrigated agricultural productivity (Hassan *et al.*, 2002). However, the adoption of deficit irrigation strategies is generally difficult and requires not only good irrigation scheduling decisions but also appropriate evaluation of the economic impacts at the farm level (El Amami *et al.*, 2001).

From an engineering perspective, dealing with deficit irrigation is difficult without incurring yield reductions since water stress imposed at any growth stage will generally lower the efficiency of the water used in crop transpiration (English, 1990; Lamm *et al.*, 1994). The relationship between crop yield and water applied is complicated due to the fact that yield may depend either on when water is applied or on the amount of water applied (English and Nakamura, 1989; Zhang and Pei, 2002). Therefore, the observed crop growth pattern is an advantageous characteristic in determining the onset of the period critical for applying deficit irrigation (Domingo *et al.*, 1996).

Under deficit irrigation, water application is dictated by crop water demand, water availability and water price such that irrigation water application can be omitted, reduced or varied widely at certain growth stages (Doorenbos and Kassam, 1986; English and Nakamura, 1989; English and Raja, 1996). As such, the adoption of deficit irrigation implies appropriate knowledge of crop water use and responses to water deficits, including the identification of critical crop growth periods and of the economic impacts of yield reduction from the irrigation water savings (English and Nakamura, 1989).

Deficit irrigation can be considered as an essential strategy for increasing on-farm water productivity in water scarce areas. The risk associated with deficit irrigation can be minimised through proper irrigation scheduling and by avoiding water stress during the growth stages in which the crop is especially sensitive to water stress (Zhang, 2003). Therefore, good irrigation scheduling decisions are required to manage deficit irrigation, some of which employ the irrigation production function approach and irrigation scheduling approach as explained under Sections 2.2.1 and 2.2.2. However, for efficient use of irrigation water, these approaches require information on the optimum time to apply limited amounts of water to crops to obtain maximum and high quality yield (Al-Kaisi *et al.*, 1997; English and Nakamura, 1989).

2.1.1 Irrigation production function approach

A production function represents the relationship between inputs and outputs in a production process and serves as a basis for describing, explaining and predicting the

output expected from a specified level of inputs (Scheierling *et al.*, 1997). It plays an important role in production decisions for water resource planning and management.

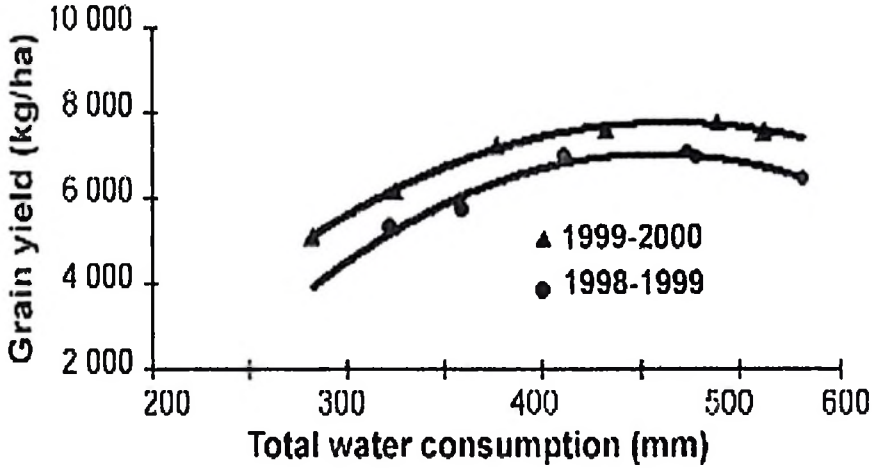

Figure 1: An example of a quadratic water production function for wheat

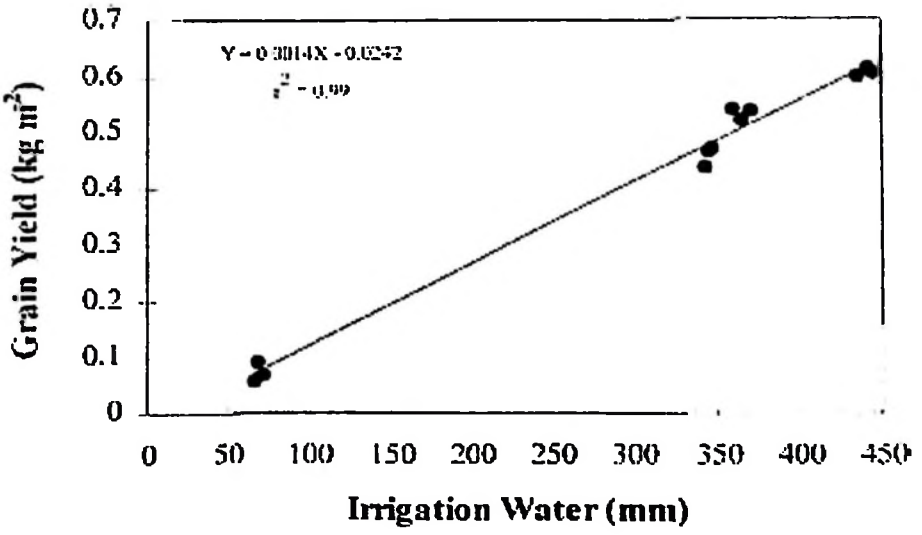

Figure 2: An example of a linear water production function for corn

The relationship between crop production and irrigation water applied is called the irrigation production function. As a result of differences in the growth habit of the different crops, many researchers have reported a quadratic irrigation production function, as in Figure 1, that implies a diminishing marginal productivity of irrigation water (Zhang. 2003; Zhang and Pei. 2002; Oweis and Hachum, 2004) while other researchers have reported a linear irrigation production function, as in Figure 2 (Irmak *et al.*, 2000).

Different views exist concerning the reliability in use of the irrigation production function under deficit irrigation. For instance, English (1990) and English and Raja (1996) emphasise that the inherent uncertainty of irrigation production functions makes it virtually impossible to predict yields exactly; hence, it is impossible to know precisely what level of water use will maximise net profits. The production function will only be an estimate of the true relationship because yields are affected by a number of unpredictable factors that include climate, germination rate and incidence of diseases (English and Raja, 1996). Oweis and Hachum (2004) expressed that the use of irrigation production functions in deficit irrigation makes it difficult to coincide irrigation schedules with the crop moisture sensitive stages since the time of irrigation water application cannot be determined in advance.

However, the risk with using irrigation production functions in deficit irrigation is low because the response curve of crop yield to water supply often has a wide plateau and hence a considerable amount of water can be saved with insignificant yield reduction compared with full irrigation (Zhang, 2003). Therefore, despite

several of the shortfalls, other researchers still maintain that the irrigation production function becomes very useful in deficit irrigation and its application in several cases has yielded successful results. For instance, Zhang and Pei (2002) scheduled deficit irrigation for winter wheat in China using the irrigation production function and found that the total irrigation amount for maximum profit was lower than the amount for maximum yield. Oweis and Hachum (2004) developed and used quadratic production functions to evaluate optimal irrigation levels to maximise profit in wheat and found that profits were maximised under deficit irrigation.

2.1.2 Irrigation scheduling approach

Deficit irrigation implies the adoption of appropriate irrigation schedules that are built upon validated irrigation scheduling models or are based on extensive field trials (Perreira *et al.*, 2002). Therefore, various techniques can be used for scheduling deficit irrigation to monitor soil moisture contents with successful results. Among the notable techniques are the neutron probe (Zhang and Pei, 2002), tensiometer readings (Moutonnet, 2002), the gravimetric method (Nautiyal *et al.*, 1999), a stochastic model for soil moisture (Mukherjee and Kottegoda, 1992) and a theoretical procedure using a water stress sensitivity index (Ghahraman and Sepaskhah, 1997). However, in some cases, technical and operational constraints may limit the applicability of certain approaches (Tarimo *et al.*, 2004).

The neutron probe has long been considered an accurate method for deep measurements of porous media moisture content in the vadose zone although sometimes the determination at field scale of the daily crop water use can be very

inaccurate such that the estimated actual crop water use can be greater or less than the potential (Bertuzzi *et al.*, 1994; Kamilov *et al.*, 2002; Evett *et al.*, 2003; Evett and Steiner, 1995). However, when deficit irrigation scheduling is based on monitoring the root zone moisture content with a neutron probe, it constitutes a practical approach whereby soil moisture is replenished to an upper limit as soon as the required lower limit is reached (Stricevic and Caki 1997; Tarimo *et al.*, 2004).

In this respect, the approach constitutes monitoring the current soil moisture content, comparing it to predetermined minimum soil moisture content and irrigating to maintain soil moisture content above the minimum level (Kamilov *et al.*, 2002). The minimum soil moisture content is often varied according to the crop growth stage with respect to the crop sensitivity to water stress at the particular growth stage as significant crop stress occurs below a threshold value of soil water depletion (Stricevic and Caki 1997; Zhang, 2002). Through frequent assessment of the root zone soil moisture, the planned soil moisture deficits should prevent prolonged crop water stress to avoid retarding crop growth and they should be predictable in order to irrigate efficiently (Boonyatharokul and Walker, 1979).

The calculation of the irrigation water depth for irrigation scheduling methods involves the knowledge of the actual soil moisture content before irrigation, of the moisture content at field capacity and permanent wilting point, or the complete moisture release curve and the variability of these properties within the field to be irrigated is of extreme importance (Reichardt *et al.*, 2001; Steel *et al.*, 1997). However, where more detailed hydraulic characterisation cannot be performed,

estimates of total soil moisture content at field capacity can be based on the neutron probe measurements at the beginning of the study (Kamilov *et al.*, 2002; Carrijo and Cuenca, 1992).

The checkbook method for irrigation scheduling can then be used to accurately schedule irrigations. This method requires knowledge of daily water use, rooting depth, soil water holding capacity and periodic soil moisture content measurements (Ashley *et al.*, 1998). When using the checkbook method approach, daily crop water use is recorded on a soil moisture balance sheet and the available moisture is calculated. A minimum acceptable soil moisture level is determined based on the soil type, crop growth stage, and the effective root zone depth. Irrigation water is applied when the soil moisture is drawn down to a predetermined level.

2.2 Economic aspects of deficit irrigation

A number of researchers have analysed the economics of deficit irrigation in specific circumstances and have concluded that this technique can increase farm profit as a result of increased irrigation efficiency, reduced irrigation costs and the opportunity cost of water (English and Raja, 1996; Perreira, 1999). Improvements in water use efficiency and water productivity are essential if the economic benefits from deficit irrigation are to be realised (Shideed *et al.*, 2003). The economic use of water depends largely on the management of water deployment and application, and on the technical, economic, and socio-cultural conditions (Wolff and Stein, 1999).

The cost of water is the single most important factor in the economics of deficit irrigation since with the increasing shortage of water in many countries, irrigation water fee may increase whereas grain prices may decrease or remain constant because of several reasons (Shideed *et al.*, 2003; Zhang and Pei, 2002). Optimising irrigation water use would become a top priority under such circumstances. However, in some countries water from public irrigation schemes is provided free to users such that costs of inputs other than water become important in deriving the economic productivity from the irrigation activity (El Amami *et al.*, 2001; Shideed *et al.*, 2003).

Deficit irrigation is one of the methods recommended as a means of improving the economic use of irrigation water (Wolff and Stein, 1999). The economic water use efficiency under deficit irrigation is enhanced by reallocating water from an economically less productive application to one of greater economic value through the reduction of the amount of water consumed per unit of crop yield (Shideed *et al.*, 2003). In economic terms, cost reduction through deficit irrigation may be geared to maximising the financial profit per hectare of land or per cubic meter of water used.

Deficit irrigation scheduling reduces the amount of water used to irrigate crops and the maximum profit from a crop can be obtained using less water than is needed for maximum yield (Zhang and Pei, 2002; Orloff *et al.*, 2003). In order to assess the impacts of deficit irrigation strategies on net income, it is important to determine the optimal allocation of water resources that would maximize net income considering the availability of land, labour and water (El Amami *et al.*, 2001). Economic analysis

of irrigation water use under deficit irrigation assumes that all quantities of inputs and outputs are proportional to the level of the activity (Shideed *et al.*, 2003).

However, a sensitivity analysis relative to the price of water and the price of the products may be helpful to understand better how the feasibility of deficit irrigation is affected (El Amami *et al.*, 2001). The lower threshold levels of irrigation water at which economic benefits with deficit irrigation are achieved are varied with crops. The variations relate to the costs of production and yield values such that the thresholds are higher when the yield reductions are smaller (El Amami *et al.*, 2001).

To assess the economic contribution of irrigation water, several existing methods used have their own context of applicability depending largely on the nature of the data available. Some of the methods include the integrating demand function, the residual imputation concept, the value-added concept, and the alternative cost concept (Agudelo and Hoekstra, 2001). In measuring the economic contribution of irrigation water according to the value added concept, the monetary value of crop production attained per unit of water used or consumed throughout the production process is used. With the same amount of water available, from the two most important irrigation scenarios (i.e. production maximisation by full irrigation and profit maximisation with limited water by deficit irrigation), using the principles developed by English and Raja (1996) and Zhang and Oweis (1999), deficit irrigation improves the economic productivity of water in many crops (Zhang, 2003).

2.2.1 Target function approach for profit maximisation

Optimum use of irrigation water for maximum profit under deficit irrigation is essential if the economic benefits from deficit irrigation are to be realised (Al-Kaisi *et al.*, 1997). A target function approach was developed for use in identifying the profit optimisation level with irrigation water. In this approach, the target function is the amount of irrigation water that maximises profits per unit area and is given as follows (Zhang and Pei, 2002):

$$I^* = \max(B - C) \quad \text{.....(1)}$$

where I* = maximum profit per unit area ($/ha)

B = total output value per unit area ($/ha)

C = total input value per unit area ($/ha)

The following equations yield the values of B and C (Zhang and Pei, 2002):

$$B = Y(P_{Y1} + P_{Y2}L) \quad \text{.....(2)}$$

$$C = W(P_{W1} + P_{W2}) + K(D_W + D_Y) + F_c \quad \text{.....(3)}$$

where Y = yield (kg/ha)

W = total irrigation water (m^3/ha)

K = labour cost per person ($/day)

F_C = seed, sowing, fertiliser, etc costs ($/ha)

P_{Y1}, P_{Y2} = grain and straw price (\$/kg)

P_{W1}, P_{W2} = water fee, energy cost (\$/m^3)

D_W, D_Y = days needed for irrigation, harvesting

L = ratio of straw yield to grain yield

The effect of water deficit on yield is calculated based on the Jensen (1968) model:

$$Y = Y_m \prod_{i=1}^{n} \left(\frac{ET_i}{ET_{im}} \right)^{\lambda_i} \quad \text{.....(4)}$$

where Y = simulated yield (kg/ha)

Y_m = maximum yield (kg/ha)

ET_i = crop water used at stage i (m^3/ha)

ET_{im} = crop water used at stage i in stress free (m^3/ha)

λ_i = sensitivity index to water stress at stage i

Let: $$(P_{Y1} + P_{Y2} L) = M \quad \text{.....(5)}$$

$$(P_{W1} + P_{W2}) = N \quad \text{.....(6)}$$

$$W = \sum_{i=1}^{n} W_i \qquad i = 1, 2, \ldots n. \quad \text{.....(7)}$$

Substituting Equations (2), (3), (4), (5). (6), and (7) into Equation (1), yields the following target function (Zhang and Pei. 2002):

$$I^* = \left\{ MY_m \prod_{i=1}^{n} \left(\frac{ET_i}{ET_{im}} \right)^{\lambda_i} - N \sum_{i=1}^{n} W_i - F_c \right\} \quad \text{.....(8)}$$

where M, N = target coefficients ($/ha)

W_i = irrigation at stage i (m^3/ha)

λ_i = sensitivity index at stage i

2.2.2 Irrigation production function for profit maximisation

Determining irrigation production functions is the basis for economical water productivity and the objective of its use is to determine the optimal amount of irrigation that results in maximum profits (Oweis and Hachum, 2004). When the cost of irrigation water and the expected unit price for the product are known, maximum profit occurs where the marginal productivity for water equals the price ratio of water to the product (Zhang and Pei, 2002).

The model for the quadratic irrigation production function is given as follows (Scheierling *et al.*, 1997; Adiku *et al.*, 2001; Oweis and Hachum, 2004):

$$Y = b_0 + b_1 W + b_2 W^2 \quad \text{.....(9)}$$

where Y = yield (kg/ha)

W = total irrigation water (mm)

b_0, b_1, b_2 = regression coefficients in production function

This model suggests that yield increases with irrigation water can be considered in three phases. In the first phase, the value of the increased yield exceeds the increase in cost. In the second phase, the value of the increased yield is equal to the increase in cost. In the third phase, the increase in yield is of less value than the increase in cost (Zhang and Pei, 2002).

The interpretation is that with increase in irrigation water applied, profits increase in the first phase, peak in the second phase, and decrease in the third phase. The optimum level of applied water for a particular situation is that which produces the maximum profit or crop yield, per unit of land or per unit of water, depending on the underlying objective function and the limiting constraint (Shideed *et al.*, 2003). Therefore, the irrigation amount for maximum profit is derived from the second phase as follows (Zhang and Pei, 2002):

$$W = \frac{\left(\frac{P_W}{P_Y} - b_1\right)}{2b_2} \qquad \text{.....(10)}$$

where

W	=	irrigation for maximum profit (mm)
P_W	=	unit price of water ($/m^3)
P_Y	=	unit price of grain ($/kg)
b_1, b_2	=	regression coefficients in Equation (9)

The use of an irrigation production function derived from experiments can be used to calculate economic benefits of application of different irrigation depths by means of a well-established analytical economic method (English, 1990). However, the limitation is that usually irrigation production functions are derived from only one specific season and therefore do not represent the variability on yield due to climatic variability over the long term for a given site. The optimal irrigation depth varies seasonally because of seasonal variations in climatic conditions for a particular site. Therefore, irrigation production functions relate yield as a function of seasonally applied water and yield.

2.3 Varietal and physiological response to deficit irrigation

Most of the crop responses to water deficit have a negative effect on production, but crops have different and often complex mechanisms to react to shortages of water (Doorenbos and Kassam, 1986). In many cases, irrigation deficits during the vegetative growth stage have less impact on biomass production than during reproductive stages (Pandey *et al.*, 2000, Scheierling *et al.*, 1997).

In a study to identify how to minimise water use by applying RDI during phenological stages of peaches least sensitive to water deficit, Dichio *et al.* (2004) found that there were no significant reductions in yield and quality for a RDI treatment and the control. Hassan *et al.* (2002) found that water deficit at vegetative and maturity stages of potato produced sharp decreases in potato yield. Romero *et al.* (2004) found that RDI had no effect on kernel size of mature almond trees. Nautiyal *et al.* (1999) found that water use efficiency and dry matter production including

economic yield of groundnut was increased by imposing transient soil moisture deficit during vegetative stage.

Doorenbos and Kassam (1986) found that a reduction in water supply during the vegetative period of cotton hastened flowering and boll formation, just as it enhanced flower bud formation and checked excess vegetative growth in citrus. Domingo *et al.* (1996) found that neither physical nor chemical lemon characteristics were significantly modified when RDI reduced irrigation amount during the season except in the rapid fruit growth period. Orloff *et al.* (2003) found that although there were statistically significant effects on forage quality of alfalfa due to deficit irrigation, yield reduction was not severe considering the amount of water saved. Zhang *et al.* (2006) found that RDI improved length of wheat spike, fertile spikelet number, grain weight per spike and number of grains which indicated that these four yield components may be a combined result of higher 1000-seed weight and finally higher grain yield.

Mastrorilli *et al.* (1995) found grain sorghum to be highly sensitive to water stress during the flowering stage as stress at this stage reduced final biomass by 52%, number of seeds per panicle by 58% and grain yield by 61%. However, water stress after flowering did not severely reduce the final grain yield and its components. Pandey *et al.* (2000) found that under deficit irrigation during the vegetative stage alone, grain yield of maize was reduced by 11% while significant yield reductions of 23-26% were found for two consecutive seasons when deficit irrigation occurred

during both the vegetative and early reproductive stage. Yield reductions were associated with the reduction in kernel numbers and, to a lesser extent, kernel weight.

Some studies have found that higher levels of water stress are needed to reduce some attributes of a crop response variable and have suggested that irrigation deficits during the vegetative growth stages reduce leaf area, leaf and stem weight thereby slowing down crop growth rate, plant height, shoot dry matter and harvest index (Pandey *et al.*, 2000; Mastrorilli *et al.*, 1995). When evapotranspiration deficit exceeds 50%, all of these growth parameters are affected because of a gross reduction in assimilation partitioning; causing increased allocation to roots as well as acceleration of leaf senescence in direct proportion to the degree of water stress (Arora and Gajri, 2000; Adiku *et al.*, 2001; Blum, 2004).

For example, McCarthy *et al.* (2002) found that higher levels of stress in vines were needed to reduce berry size compared with vegetative growth. Gonzalez and Castel (2004) found no effect on fruit yield or quality in citrus orchards under RDI. In orchards. Goldhamer (2000) found that the RDI treatments that imposed water deficits early in the season resulted in slower fruit growth rates. After full irrigation was reintroduced, fruit growth accelerated and remained relatively high though tree water status had not recovered. Romero *et al.* (2004) found that long-term water stress led to a progressive decline in stomata conductance, assimilation rate and transpiration rate of mature almond trees. In the same study, severe water stress during the kernel-filling stage resulted in premature defoliation and a reduction in leaf growth rate, which decreased tree leaf area. However, not all deficit irrigation

strategies have had positive impacts although it depends on the crop stage in which it is sensitive to water stress. For instance, Hassan *et al.* (2002) found that deficit irrigation during the vegetative stages had produced detrimental effects on potato yield and quality.

2.4 Crop sensitivity to water stress

Water stress of a crop depends on the stored profile soil moisture and the crop yield is also directly affected by the spatial distribution of soil moisture content (El Amami *et al.*, 2001). The decrease in crop yield is related to the sensitivity of the crop to water stress depending on when stress was introduced or on the magnitude of the stress (Doorenbos and Kassam, 1986; English and Nakamura, 1989).

Knowledge of the sensitivity of a crop to water stress during a particular growth stage has been widely used in studies aiming at developing deficit irrigation strategies and determining the yield response factor (λ_y). The yield response factor is a parameter used to quantify the effect of water stress that is derived from the linear relationship between relative seasonal evapotranspiration deficits and relative yield loss (Doorenbos and Kassam, 1986). A mathematical relationship between relative seasonal evapotranspiration and relative yield loss was developed and has extensively been used in many studies to evaluate the sensitivity of deficit irrigation on crop yield and the standard formulation is given as follows (Zhang *et al.*, 2002; George *et al.*, 2000; Moutonnet, 2002):

$$1-\frac{Y_a}{Y_m}=\lambda_y\left(1-\frac{ET_a}{ET_m}\right) \qquad \text{.....(11)}$$

where Y_a = the actual harvested yield (kg/ha)

Y_m = the maximum harvested yield (kg/ha)

ET_a = the actual evapotranspiration (mm)

ET_m = the maximum evapotranspiration (mm)

λ_y = the yield response factor

Calculation of Y_a, Y_m, ET_m and ET_a is well documented and the λ_y values for some selected field crops are also presented in the literature (Doorenbos and Kassam, 1986). Where the available water supply does not meet the full moisture requirements of the crop, it is possible to estimate the λ_y using Equation (11). Generally, higher estimated λ_y values imply that in-field deficit irrigation practices had a higher impact on crop yield (Moutonnet, 2002; Zhang, 2002).

2.5 Performance evaluation of irrigation systems

Performance of an irrigation system is evaluated for a variety of reasons and the performance measure used indicates how well the system is performing relative to other systems (Molden and Gates, 1990). Since water is the most limiting resource in an irrigation system, most performance indicators are somehow related to the amount of water applied or used (Brito *et al.*, 2003). In that respect, numerous definitions dealing with the evaluation of irrigation water use exist of which many are not

essentially different from one another such that their use should be turned to the purpose of the evaluation (Sanaee-Jahromi *et al.*, 2001; Burton *et al.*, 1999).

The International Water Management Institute (IWMI) developed a set of process and comparative performance indicators that are most useful in assessing and revealing the technical efficiency and utility of irrigation water use that can be used to evaluate irrigation performance within a system or across systems (Molden and Gates, 1990; Kloezen and Restrepo, 1998). The aim of developing performance indicators was to evaluate impacts of management intervention and to provide a basis for identification of how a system is performing by measuring outputs of irrigated agriculture (Bos, 2000). The main objectives of using comparative indicators as compared to process indicators are to evaluate outputs and impacts of intervention in an individual system, to compare performance of a system over time, and to allow comparison of systems in different areas and at different system levels (Molden *et al.*, 2003; Kloezen and Restrepo, 1998).

Performance indicators used in evaluating irrigation systems have been broadly classified into three groups: hydraulic, agricultural, and socio-economic (Saleh and Mondal, 2001). From these three groups, agricultural indicators measure the contribution of the irrigation activity to the economy in relation to consumption of the increasingly scarce water by directly reflecting the main output of the major inputs in an irrigated agricultural system (Molden *et al.*, 1998). Typically, the performance indicator chosen for evaluation depends on the purpose and objective of

the assessment in which relative comparison of values at least allows an examination of how well a system is performing relative to other systems (Bos, 2000).

Water use efficiency and water productivity are important agricultural performance indicators that are used in assessing the impact of water management strategies and practices used to produce more crops with less water (Sanaee-Jahromi *et al.*, 2001). It is vital to specify the water use components when deriving water use efficiency and productivity to avoid the confusion over the two since these terms are related but are not essentially the same (Shideed *et al.*, 2003).

2.5.1 Water use efficiency

Transformation of an input into an output is generally referred to as efficiency. Depending on the intended purpose and the domain of interest, many efficiency concepts are involved, such as water application efficiency and crop water use efficiency (Howell, 2001). In irrigation engineering terms, water use efficiency is defined as the ratio between the amount of water required to grow a crop (i.e. evapotranspiration, percolation and seepage, leaching for salinity control and land preparation) and the total amount of water input within a spatial domain of interest (Howell, 2001; Seckler *et al.*, 2000; Shideed *et al.*, 2003). However, from an agronomic perspective, water use efficiency (WUE) is generally defined as the ratio between crop yield (usually economic yield) and water used (evapotranspiration or applied water) to produce that yield (Ahmad *et al.*, 2004). The agronomic focus therefore illustrates the concept of crop water use efficiency (CWUE) with reference

to the fraction of water stored in the root zone that is transpired by the crop (Saleh and Mondal, 2001; Seckler *et al.*, 2000).

The CWUE concept is not directly related to the amount of output that can be produced with an amount of available water as a sizeable portion of irrigation water may be lost by evaporation without passing through transpiration resulting in lower water use (Shideed *et al.*, 2003; Pandey *et al.*, 2000). This is particularly evident when the crop canopy is not well developed and the ground is not covered. The maximum crop yield does not correspond to the highest crop water use efficiency (Shao *et al.*, 2002). However, CWUE generally tends to increase with a decline in irrigation if the water deficit does not occur at single growth stage of the crop that enhances total crop water use (Howell, 2001).

A potentially wide range of factors can deplete water. Beneficial depletion includes consumption by the crop being irrigated while non-beneficial depletion includes evaporation and flows to sinks such as the sea. A higher level of efficiency can be achieved by lowering non-beneficial depletion (Barker *et al.*, 2003). However, such a high efficiency does not imply a high level of productivity or economic return. The same degree of beneficial utilisation may have substantially different values for the productivity of the water since the same amount of water depleted in the irrigation of one crop may have a much higher value in another crop or non-agricultural use (Shideed *et al.*, 2003; Pandey *et al.*, 2000).

Because water use efficiency from an agronomic perspective differs from the engineering definition due to the different connotations attached to the term efficiency, the term water use efficiency has probably outlived its usefulness (Seckler *et al.*, 2000). Some of the definitions and interpretation of the new terminologies used in the water accounting relating to the engineers view of efficiency are still not widely understood (Kijne *et al.*, 2003). As a result, the water productivity concept is used more widely and commonly, as it is relatively easy to measure the return from limited water (Barker *et al.*, 2003).

2.5.2 Water productivity

Productivity, in general, is a ratio referring to the unit of output per unit of input (Barker *et al.*, 2003; Sanaee-Jahromi *et al.*, 2001; Bos, 2000; Kijne *et al* (2003). Until recently, water was not considered a scarce resource. Now with mounting water shortages and water quality concerns, there is growing interest in measures to increase water productivity (WP), commonly measured as crop output per unit volume of water. Thus, WP (yield or net economical return per unit volume of water consumed) is a good indicator for assessing performance of irrigation systems and management practices, comparing different irrigation systems, and evaluating the existing performance and exploring options for water savings (Ahmad *et al.*, 2004; Zhang and Oweis, 1999).

In deriving WP, the denominator remains the quantity of water diverted or depleted; however, the numerator can be expressed in general physical or economic terms (i.e. mass or monetary value of produce per unit volume of water) (Ahmad *et al.*, 2004).

Because the water used may have various components such as evaporation, transpiration, gross or net inflow, it is essential to specify which components are included in the calculation (Oweis and Hachum, 2004; Shideed *et al.*, 2003). There are several different ways of expressing WP most of which fall under the following broad classes (Barker *et al.*, 2003):

a) Pure physical productivity = quantity of the product divided by the quantity of the water diverted or depleted.

b) Combined physical and economic productivity = economic value either the gross or net present value of the product divided by the amount of the water diverted or depleted.

c) Economic productivity = gross or net present value of the product divided by the value of the water either diverted or depleted.

The physical water productivity indicator alone is not sufficient to assess the economic level of water use, as water is used in combination with a large set of other inputs (e.g. land, fertilizers, labour, machinery, and management) to produce yields (Ahmad *et al.*, 2004). The economically efficient amount of water use depends on the relative prices of water and other inputs, the marginal products of the inputs, the prices of inputs and the amounts of other inputs (Oweis and Hachum, 2004). Therefore, singling out any one input such as water to determine productivity is not helpful and potentially misleading. As a result, the economic water productivity is also considered.

The Standardised Gross Value of Production (SGVP) is the output of the irrigated area in terms of the gross or net value of production measured at local or world prices (Bos, 2000). SGVP is used when deriving the economic productivity of water where the interest is the measurement of production from irrigated agriculture that can be used to compare performance across systems or between different years. Therefore, to compare different crops in different regions and/or years, WP needs to be expressed as SGVP per unit of water depleted ($/m^3) to overcome the difficulty that arises when comparing different crops as obviously there are differences in local prices at different market locations and/or years throughout the world (Molden *et al.*, 2003; Bos, 2000; Degirmenci *et al.* 2003). However, when considering only one irrigation system or irrigation systems in a region where prices of compared crops are similar, WP can be measured using the net value of production (NVP) and gross value of production (GVP) using the local prices (Sakthivadivel *et al.*, 1999).

2.6 Trends in water productivity

In general, functions relating output to input (e.g. water, fertiliser) are nearly always concave because the use of higher levels of input is eventually subject to diminishing returns. Under these circumstances, high WP may simply reflect a shortage of water rather than good management or economic efficiency (Barker *et al.*, 2003). In fact, when such a function is purely concave, productivity is maximised by using as little input as possible, even when it results in large declines in output. Thus, the goal should be to optimise water productivity, not maximise it. The association of high WP values with high yields has important implications in crop management for achieving efficient use of water resources in water scarce areas (Sarwar and Perry,

2002). At the same time, attaining higher yields with increased WP is only economical when the increased gains in crop yield are not offset by increased costs of other inputs (Zhang and Oweis, 1999).

When water is in short supply, its productivity is substantially increased through deficit irrigation (English, 1990). In several situations, the 50% depletion level of available soil moisture has been reported to be the critical point of many soils beyond which yields were reduced (Lamm *et al.*, 1994; Martin *et al.*, 1991). On the other hand, the 50-60% replacement of total crop water requirements was found as the critical range in which WP realises acceptable yields under deficit irrigation (Sarwar and Perry, 2002; Dichio *et al.*, 2004).

The relationship between crop yield and WP demonstrate that higher WP is achieved at a level of water applied that is lower than that at maximum yield (Zhang, 2003). Many irrigation experiments involving different irrigation water levels have also shown that deficit irrigation usually has higher WP of applied water than full irrigation. There is almost a linear relationship between yield and WP per unit water transpired. However, the characteristic of the curve showing the relationship between WP and water applied differs among crops (Zhang, 2003). In other crops, such as wheat, WP of applied water increases sharply at a low water supply level and reaches a maximum at a certain level of water supply. After its maximum, WP of applied water decreases with increasing water supply, depending on the response of yield to water. In addition, the level of water application at the maximum WP of applied water differs considerably for different locations (Oweis and Hachum, 2004).

2.7 Options for improving water productivity

Improving WP is a better strategy for improved agricultural productivity in water scarce areas and requires a better matching of water application to crop needs, in terms of both timing and quantity (Howell, 2001; Oweis and Hachum, 2004). For instance, the WP of applied water can be 1 kg/m^3 in wheat (Zhang, 2002), 0.4-0.5 kg/m^3 in grain legumes (Zhang and Oweis, 1999), 0.37-0.68 kg/m^3 in rice (Tuong and Bhuiyan, 1999), 1.2-1.3 kg/m^3 in maize (Droogers *et al.*, 2000) and 0.4 kg/m^3 in cotton (Zhang, 2003).

The options available for improving on-farm irrigation WP include agronomic, engineering, management and institutional approaches (Howell, 2001). The on-farm WP can be increased either by reducing the water inputs that do not contribute to the yield formation or by increasing crop yield. The first strategy entails mainly deficit irrigation, while the second relies on agronomic improvement (Tuong and Bhuiyan, 1999). There has been steady improvement in grain yield per hectare through plant breeding over the last century that did not aim at increasing WP (Barker *et al.*, 2003). Nevertheless, it has indirectly contributed to increase in WP because yields have increased together with the reduction in crop growth duration and hence seasonal crop water use (Kijne *et al.*, 2003).

The modern varieties developed have about a threefold increase in WP compared with the traditional varieties. The development of short season varieties has also been a major source of water savings and of increase in WP (Kijne *et al.*, 2003). For instance, the adoption of the early maturity hybrid varieties of rice, which have 15-

20% higher yield potentials than inbred varieties of comparable maturity periods, have increased average yield and reduced crop duration with a 21% reduction in crop water use (Tuong and Bhuiyan, 1999).

2.8 Water savings under deficit irrigation

The water savings from the deficit irrigation treatments can be established by comparing water applied under deficit irrigation to that applied in a well-watered control or reference treatment. The volume of water that can be saved using a deficit irrigation strategy over full irrigation is dependent on the climatic demand, stored available water and the irrigation strategy used (Prichard, 2004).

Significant savings in irrigation water under deficit irrigation were found in several studies without affecting yield and its components including quality and improved water use efficiency (FAO, 2002; Zhang and Pei, 2002; Zhang, 2002). Around 6-22% of irrigation water was saved in citrus orchard (Gonzalez and Castel, 2004), 60% in apple trees (Mpelasoka *et al.*, 2001), around 30% in mature almond trees (Romero *et al.*, 2004), around 9-26% in Frost Nucellar trees (Goldhamer, 2000), and about 30% in lemon trees (Domingo *et al.*, 1996).

However, water savings do not necessarily lead to higher water productivity and, similarly, higher water productivity does not lead to greater economic efficiency (Barker *et al.*, 2003). When either the water productivity values under deficit irrigation are lower than the values for the optimum condition or there are no significant differences in values of deficit irrigation treatments and the optimum

condition, no benefits occurred in terms of water resource conservation by imposing the water deficits (FAO, 2002; Lamm *et al.*, 1994; Pandey *et al.*, 2000).

Seckler (1999) distinguishes between dry and wet water savings. A reduction in crop water use is a wet saving because the evapotranspired water is lost for future use in the basin while irrigation water savings are dry savings as the water may be recycled within the basin for future use unless it is polluted. Losses in individual irrigation schemes in upper streams partly return to the water network and are available for the downstream users (Seckler, 1999; Perry, 1999). Hence the real potential for water saving in the whole river basin could be lower than in a specific scheme.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of the study area

3.1.1 Location

This study was conducted at Herman canal irrigation scheme, an indigenous type of irrigation scheme within Chimala Ward. The Herman canal irrigation scheme lies between latitudes 8°77'S and 9°09'S and between longitudes 33°48'E and 34°06'E at an altitude of 1000 m to 1150 m above sea level (Hazelwood and Livingstone, 1982).

The scheme is situated within the Chimala catchment, about 800 km southwest of Dar es Salaam in Tanzania. The Chimala catchment is a sub-catchment of the extensive alluvial Usangu Plains bounded to the south by the Mporoto-Chimala Escarpment (Hazelwood and Livingstone, 1978). The Usangu Plains are located in the western arm of the Rift Valley and forms part of the Rufiji Basin. Figure 3 shows the location map of Herman canal irrigation scheme.

3.1.2 Climate

The rainfall in Usangu Plains is unimodal and erratic, concentrated within the period December to May. The rain starts as early as mid-October but sometimes delays until early December. Annual rainfall is highly variable from one year to another but the mean annual rainfall is 900 mm. Temperatures are highest in October/November and lowest in June/July when the minimum and maximum daily temperature varies from 12-19°C and 28-32°C, respectively (Hazelwood and Livingstone, 1982).

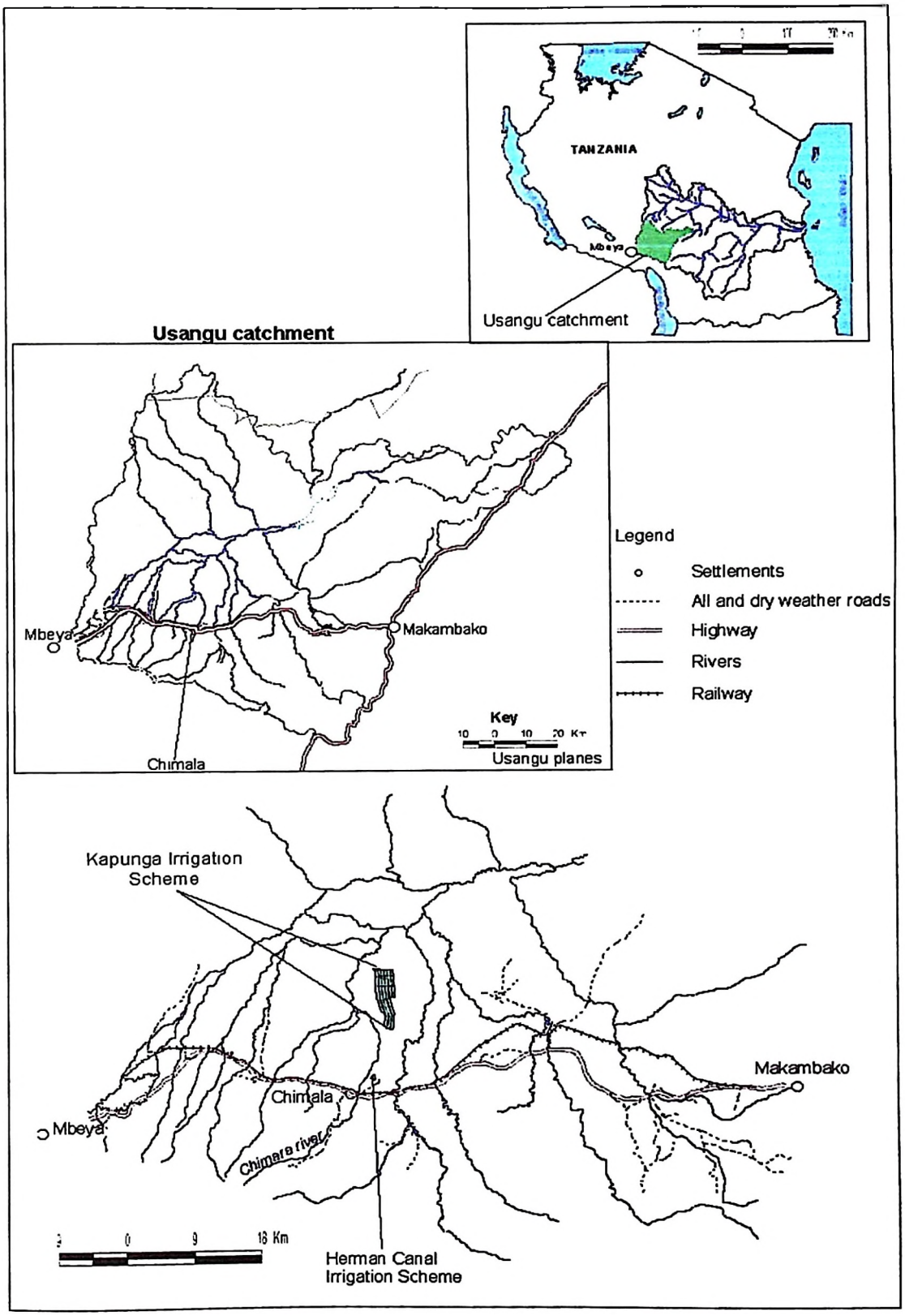

Figure 3: Location map of Herman canal irrigation scheme

3.1.3 Soils

The soils of the Usangu Plains in general consist of fertile alluvial clays. clay loams, loams and alluvial sandy clays that can extend to depths of more than 3m (Hazelwood and Livingstone, 1978).

3.1.4 Irrigation water source

The Herman canal irrigation scheme diverts water from the Chimala River through a permanent main canal intake structure and distributes the water to an area of more than 200 ha that is served by eight branch canals, *viz.* Sharbeck, Kamwene, Cheusi, Ng'ondya, Mwankunja, Nenge, Kahemele and Mengo. The Chimala River is one of the important perennial rivers in the Usangu Plains that flows from the Mporoto-Chimala Escarpment (Machibya *et al.*, 2001).

3.2 Experimental design

The experiment was laid out in randomised complete blocks with five irrigation treatments replicated three times on the Head, Middle and Tail of the Herman irrigation canal as shown in Figure 4 and Plate 1. The Head, Middle and Tail blocks were used as replicates because in all irrigation schemes differences exist among these three locations. The Head block was located very close to the main canal while the Middle and Tail blocks were located further away from the main canal such that there was easy access to irrigation water in the Head block than the rest of the blocks. Moreover, the Middle block was at least 1 km from both the Head and the Tail blocks and the soil texture among the three locations was different.



Plate 1: Treatment layout within a typical block



Plate 2: Position of access tube inside a treatment plot

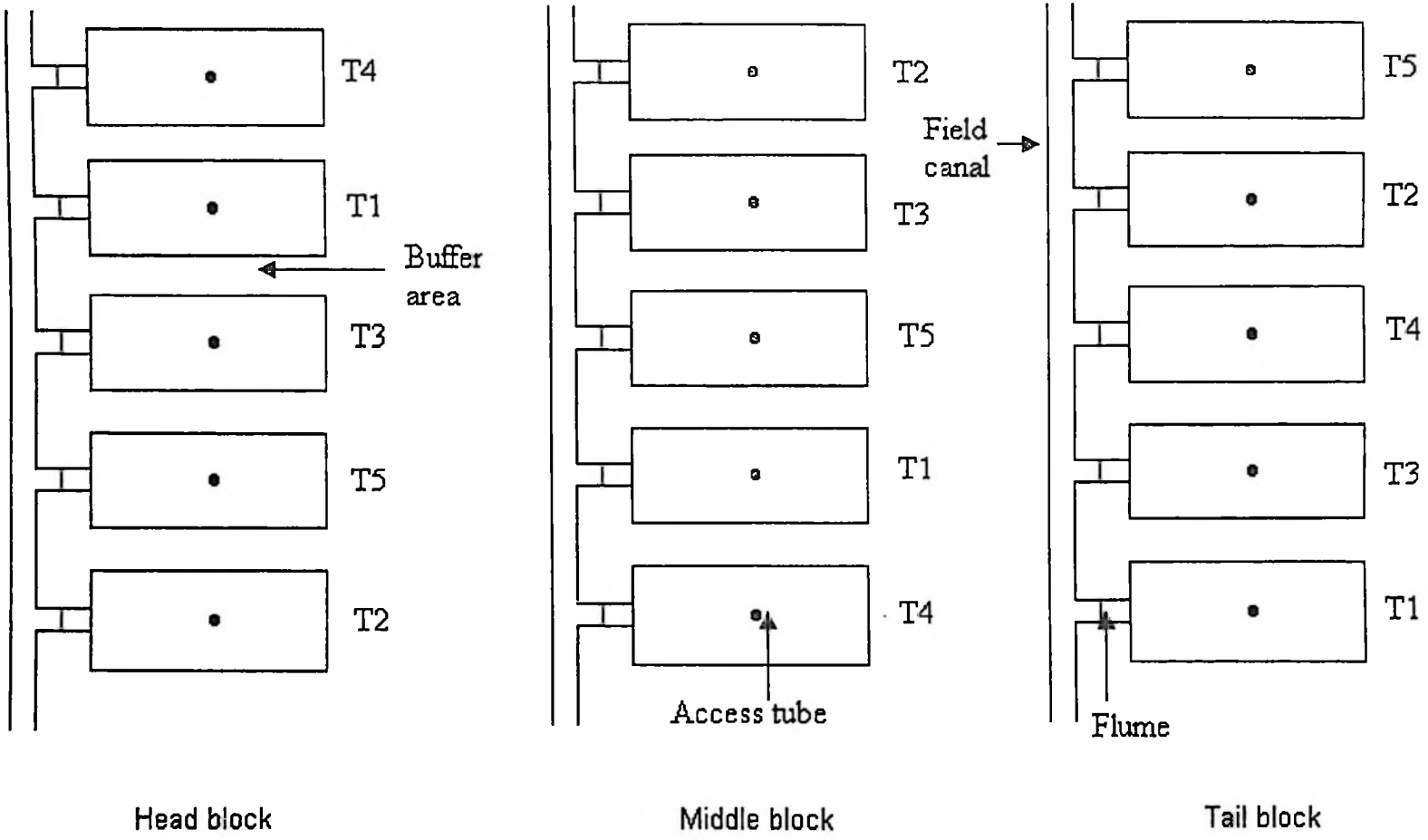

Figure 4: Randomisation of treatments within and among blocks

Experimental plots were level basins of 6 m x 3 m in area separated by a 1.5 m buffer as shown in Figure 4. An aluminium access tube was installed at the centre of each treatment plot for soil moisture content measurements using a neutron probe as shown in Plate 2.

The following were the irrigation treatments:

i. T1 treatment was farmer-managed, i.e. irrigated based on the farmer's irrigation scheduling knowledge and practices.
ii. T2 treatment was a control, irrigated after 45% depletion of total available moisture (TAM) in all growth stages throughout the experiment.
iii. T3 treatment was a RDI treatment, irrigated after 50% depletion of TAM during the pre-flowering (PRF) and post-flowering (POF) stages. During the critical flowering and pod setting stage, it was irrigated after 45% depletion of TAM.
iv. T4 treatment was a RDI treatment, irrigated after 60% depletion of TAM during the PRF and POF stages. During the critical flowering and pod setting stage, it was irrigated after 45% depletion of TAM.
v. T5 treatment was a RDI treatment, irrigated after 65% depletion of TAM during the PRF and POF stages. During the critical flowering and pod setting stage, it was irrigated after 45% depletion of TAM.

Thus, for all other treatments except the farmer-managed treatment, the soil moisture depletion level during the early and late stages was different while during the flowering and pod filling stage the depletion level was the same.

3.3 Agronomic practices

The agronomic practices were synchronised among the treatment plots to ensure uniformity. The crop used in the experiment was bean (Phaseolus *vulgaris* L.) high yielding local cultivar Wanja sown on 5th September 2004. Sowing depth was 5 cm with one seed per hole spaced at 10 cm between plants and 50 cm between crop rows. Fertiliser was applied two weeks after emergence in a form of sulphate of ammonia in one application at a rate of 110 kg/ha. Thionex pesticide was applied at emergence, two weeks after emergence and during flowering at a rate of 1.5 l/ha to control bean stem maggots, aphids and elegant grasshoppers. Weeding was carried out three weeks and six weeks after emergence. Irrigations were suspended when visual observations showed the crop had reached maturity and the crop was harvested on 5th December 2004 after 77 days from germination.

3.4 Instrumentation and measurements for data collection

3.4.1 Measurement of soil moisture content

T1 treatment was scheduled based on the farmer's knowledge while T2, T3, T4 and T5 treatments were scheduled by monitoring the root zone soil moisture content with a neutron probe (DIDCOT 3965 NE) as shown in Plate 3. Estimates of the soil moisture content at field capacity presented in Table 4 were made using the probe counts taken a day after pre-germination irrigation following the approach recommended by Kamilov *et al.* (2002) and Carrijo and Cuenca (1992) because more detailed hydraulic characteristics were not performed for the soil. Values in Table 1 by Savva and Franken (2002) were then used to support the estimates of corresponding soil moisture content at wilting point.

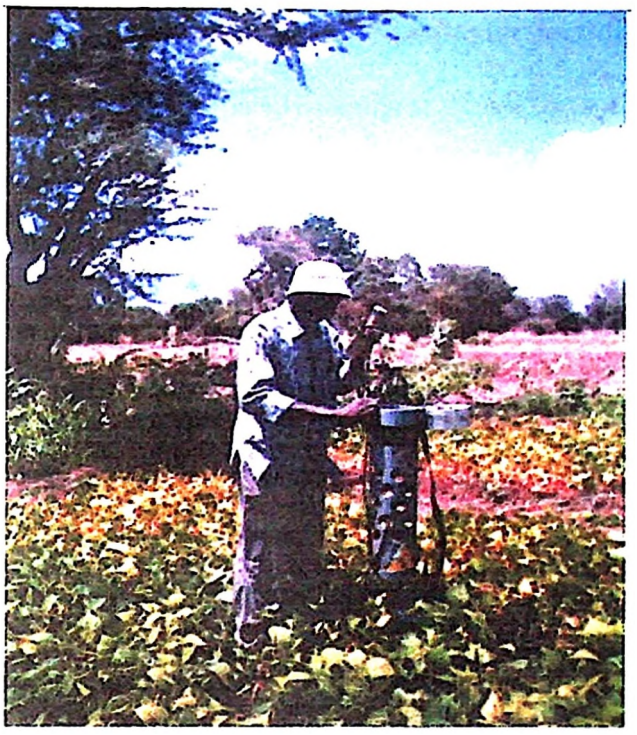

Plate 3: Measuring soil moisture in a treatment plot using a neutron probe

Table 1: Range of available moisture for different soil types

Textural class	Field capacity (vol %)	Permanent wilting point (vol %)	Available moisture (vol %)	Available moisture (mm/m)
Sandy	10-20	4-10	6-10	60-100
Sandy loam	15-27	6-12	9-15	90-150
Loam	25-36	11-17	14-19	140-190
Clay loam	31-41	15-20	16-21	160-210
Silty clay	35-46	17-23	18-23	180-230
Clay	39-49	19-24	20-25	200-250

Source: Savva and Franken (2002)

The soil moisture content in T2, T3, T4 and T5 treatments was measured daily in the morning on a volumetric basis at successive 15 cm depth intervals and the calculation of available moisture was done in the field soon after taking the neutron

counts. The 15 cm interval was regarded as the minimum depth interval for taking the neutron probe readings. The respective depths at which the soil moisture content was measured are shown in Table 2.

Table 2: Depth of soil moisture measurement with neutron probe

Root zone depth (cm)	Depth of measurement (cm)	Root zone layer represented (cm)	Measured soil layer (cm)
20	15	0 – 20	20
40	15	0 – 20	20
	30	20 – 40	20
60	15	0 – 20	20
	30	20 – 40	20
	45	40 – 60	20

The total and readily available moisture were estimated using the following equations (Kihupi, 2000):

$$TAM = 10\,D(\theta_{FC} - \theta_{WP}) \quad \text{.....(12)}$$

$$RAM = pTAM \quad \text{.....(13)}$$

where TAM = total available moisture (mm)

RAM = readily available moisture (mm)

θ_{FC} = moisture content at field capacity (% by volume)

θ_{WP} = moisture content at wilting point (% by volume)

D = root zone depth (m)

p = depletion factor (%)

TAM was not constant because of differences in soil properties among the treatment plots and locations as shown in Table 4. The soils were not homogeneous especially in the Head block.

The average of two neutron probe counts taken at a depth was used to calculate soil moisture content for the soil layer considered using the calibration equation from the manufacturer. The following calibration equation from the manufacturer was used:

$$\theta_v = 0.867\left(\frac{R}{R_w}\right) - 0.016 \qquad \text{.....(14)}$$

where θ_v = soil moisture content (% by volume)

R = neutron probe count

R_w = standard count in water

The standard count in water during the first week was read daily in a 200-litre plastic water drum before field measurements. After the first week, an average standard count was obtained from 50 counts and later used in the subsequent soil moisture content calculations throughout the experiment.

3.4.2 Calculation of available soil moisture

The available soil moisture for the respective root zone soil layers was calculated using the following equation:

$$S_a = 10 \sum_{i=1}^{n} \theta_i D \qquad \text{.....(15)}$$

where S_a = available soil moisture (mm)

θ_i = measured soil moisture content in layer i (% by volume)

D = measured root zone layer i (m)

n = number of root zone layers

The difference between TAM and RAM was the critical soil moisture content for each treatment. Therefore, when the current soil moisture content was equal to the critical soil moisture content, irrigation water was applied. Although irrigation scheduling for T1 treatment depended on the farmer's decision, the soil moisture content was also measured daily using the neutron probe.

3.4.3 Determination of application volume

The volume of water delivered to each of the RDI treatment plots was not the same at all locations. The amount depended on the readily available moisture (RAM) for each treatment plot calculated using Equation 13. The variability in RAM for each treatment within a location was due to differences in deficit levels and among locations was due to differences in soil texture. Irrigation scheduling for the RDI treatments was based on the replacement of the soil moisture deficit as per maximum allowable depletion for the particular treatment. The application volume was calculated from the following equation (Kihupi, 2000):

$$V = 10\ D_A A_u \quad \text{.....(16)}$$

where V = net irrigation volume (m^3)

D_A = net application depth (mm)

A_u = plot area (ha)

3.4.4 Measurement of discharge

Irrigation was by gravity and each discharge for the required application depth was diverted into the experimental plot from a tertially canal. The discharge was allowed into each basin at the time dictated by the soil moisture levels in the basin once the required limit was reached. The discharge was regulated along the field canal; however, high discharges were preferred than low discharges to quickly distribute the water inside the plot especially when applying low irrigation water depths.



Plate 4: Discharge measurement for treatment plot using a flume with farmers

A flume was used to measure the required net application depth for each treatment and was placed on the mouth of the basin when discharging water into the treatment plot, as shown in Plate 4, to avoid losses and erosion. The following calibration equation was used for the flume:

$$Q = 2.0474bd^{1.5} \quad \text{.....(17)}$$

where Q = discharge (l/s)

b = flume top width (mm)

d = flow depth (m)

3.4.5 Determination of water application duration

With the aid of a calculator and a timer, once irrigation water was introduced into the plot, the discharge into each plot, hence the water application duration (WAD) for the irrigation depth was immediately calculated, and irrigation was cut-off when the water application duration elapsed. After calculating discharge using Equation 17, the water application duration for the irrigation depth from Equation 16 was calculated, in seconds, using the following equation (Kihupi, 2000):

$$WAD = \frac{1000\,V}{Q} \quad \text{.....(18)}$$

where WAD = water application duration (sec)

3.5 Derivation of performance indicators

3.5.1 Water productivity

The physical ($WP_{Y_I\pi}$ and WP_{Y_ETa}) as well as the combined physical and economic ($WP_{GVP_I\pi}$ and WP_{GVP_ETa}) productivities of water were respectively calculated from the following equations (Ahmad *et al.*, 2004):

$$WP_{Y_I\pi} = \frac{Y}{I_{\pi}} \quad \text{.....(19)}$$

$$WP_{Y_ETa} = \frac{Y}{ET_a} \quad \text{.....(20)}$$

$$WP_{GVP_I\pi} = \frac{GVP}{I_{\pi}} \quad \text{.....(21)}$$

$$WP_{GVP_ETa} = \frac{GVP}{ET_a} \quad \text{.....(22)}$$

where

WP = water productivity (kg/m^3 or Tsh/m^3)

Y = yield (kg/ha)

GVP = gross value of production (Tsh/ha)

I_{π} = irrigation water applied (mm)

ET_a = seasonal crop water use (mm)

The gross value of production (GVP) was calculated as the product of grain yield (kg/ha) and grain price (Tsh/kg). During the experiment, the grain price in the study area was at Tsh 800 per kg. Seasonal crop water use was the sum of the daily crop

water use that was calculated as the difference between soil moisture content of consecutive days.

3.5.2 Irrigation water savings

The irrigation water savings with reference to the control (T2) treatment was calculated using the following equation:

$$W_s = 100\left(\frac{W_m - W_d}{W_m}\right) \quad \text{.....(23)}$$

where W_s = irrigation water saved (%)

W_m = water applied in control treatment (mm)

W_d = water applied in respective treatment (mm)

3.5.3 Yield and yield components

The average number of pods per plant for each treatment was calculated after harvesting the whole plot. From each plot, a random sample of 100 pods was shelled to determine the average number of seeds per pod. Thereafter, a 100 seeds weight was recorded from the shelled pods. Grain yield was expressed on dry basis at 10% standard moisture using a moisture-meter. First, temperature of a 200g-grain sample from each treatment was measured. Then, the sample was passed into the moisture-meter and a reading was recorded. The moisture content of the sample was read from a chart provided by the manufacturer by matching the moisture-meter reading with the sample temperature.

3.6 Yield response factor

The yield response factor calculated using Equation (11) was used to assess the sensitivity of RDI treatments. The Y_a and ET_a were the actual yield and seasonal crop water use respectively for each treatment. The Y_m and ET_m were the maximum yield and maximum seasonal crop water use from the treatments. Values for Y_m for a given area are generally taken from reported yields from nearby fields that have received high levels of crop and water management. However, considering the fact that local data for the potential yield of the Wanja bean variety were not available, data from the experimental treatments were used in the analysis.

3.7 Profit maximisation

The profit maximisation level of irrigation water was calculated from Equation (8) under Section 2.2.1 using the market price values during the time of the study. Grain revenues, irrigation water, seed, fertiliser, pesticide and labour costs were used to compute the net profit for each of the irrigation options. The labour costs were calculated from labour for land preparation, weeding and irrigation while the grain revenues were calculated from grain market price. Land preparation and weeding costs per hectare were Tsh 18 000 and Tsh 22 000, respectively, while the cost of labour to irrigate a hectare was Tsh 6000 per irrigation based on a labour cost of Tsh 1500 per person per day (4 people were projected to effectively irrigate a hectare within 6 hours of water supply). The costs per hectare of seed, fertiliser and pesticide were Tsh 78 000, Tsh 99 000 and Tsh 20 000, respectively. The market price for beans was Tsh 800 per kg of grain during the study.

The farmers were paying for irrigation water charged based on a non-volumetric fee of Tsh 3000 per hectare per year. However, another analysis for profit maximisation was made assuming water fee was charged based on the actual volume of water used. For small-scale traditional irrigation schemes such as Herman canal irrigation scheme, a price of Tsh 211 per m^3 of irrigation water was used (Hellegers, 2005).

3.8 Statistical analysis

SAS program was used to analyse the water productivity, water savings, crop water use and yield components data. Analysis of variance was run in which treatment means were separated using Duncan's Multiple Range Test. The test of significance was based on a p-value of 0.05.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Soil moisture regimes

There was spatial variability in the root zone soil properties among the three blocks as shown in Table 3.

Table 3: Physical properties of soil in the different experimental locations

Block	Root zone (cm)	Particle size distribution (%)			Bulk density (g/m^3)	Textural Class
		Sand	Silt	Clay		
Head	0 – 20	77	6	17	1.24	SL
	20 – 40	54	16	30	1.20	SCL
	40 – 60	42	25	33	1.33	SCL
Middle	0 – 20	45	18	37	1.45	CL
	20 – 40	54	13	33	1.48	SCL
	40 – 60	63	11	26	1.45	SCL
Tail	0 – 20	54	14	32	1.45	SCL
	20 – 40	52	16	32	1.38	SCL
	40 – 60	65	12	23	1.29	SCL

CL: Clay Loam; SL: Sandy Loam; SCL: Sandy Clay Loam

The average textural classification of topsoil (0–40 cm) was sandy loam in the Head block and sandy clay loam in the Middle and Tail blocks. In some treatment plots within the Head block sandy clay loam textures were present in the topsoil and sandy loam in the subsoil. Thus, the soils were generally not homogenous especially in the Head block resulting in differences in moisture content at field capacity and wilting point for the respective treatments as shown in Table 4.

Table 4: Soil moisture contents at field capacity and wilting point for respective treatments

Root zone depth (cm)	Moisture content (vol. %)	Head					Middle					Tail				
		T1	T2	T3	T4	T5	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5
0 – 20	Field capacity	15	31	15	31	31	34	34	34	34	34	24	24	24	24	24
	Wilting point	7	17	7	17	17	17	17	17	17	17	8	8	8	8	8
20 – 40	Field capacity	31	24	31	31	24	34	24	34	24	24	34	24	34	24	24
	Wilting point	17	8	17	17	8	17	8	17	8	8	17	8	17	8	8
40 – 60	Field capacity	33	24	24	24	15	24	24	24	24	24	24	24	24	24	24
	Wilting point	20	8	8	8	7	8	8	8	8	8	8	8	8	8	8

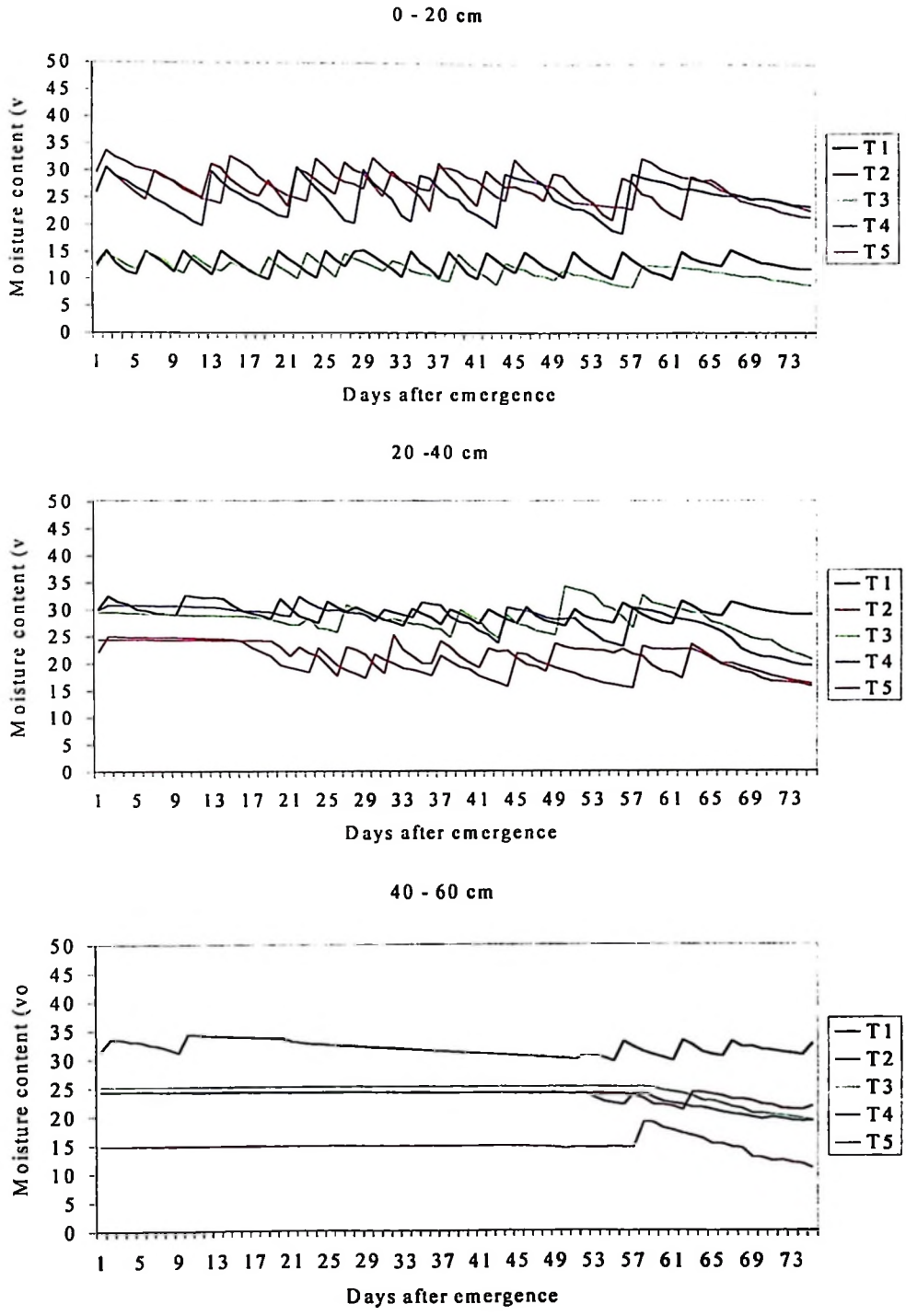

Figure 5: Soil moisture content for treatments in the Head block

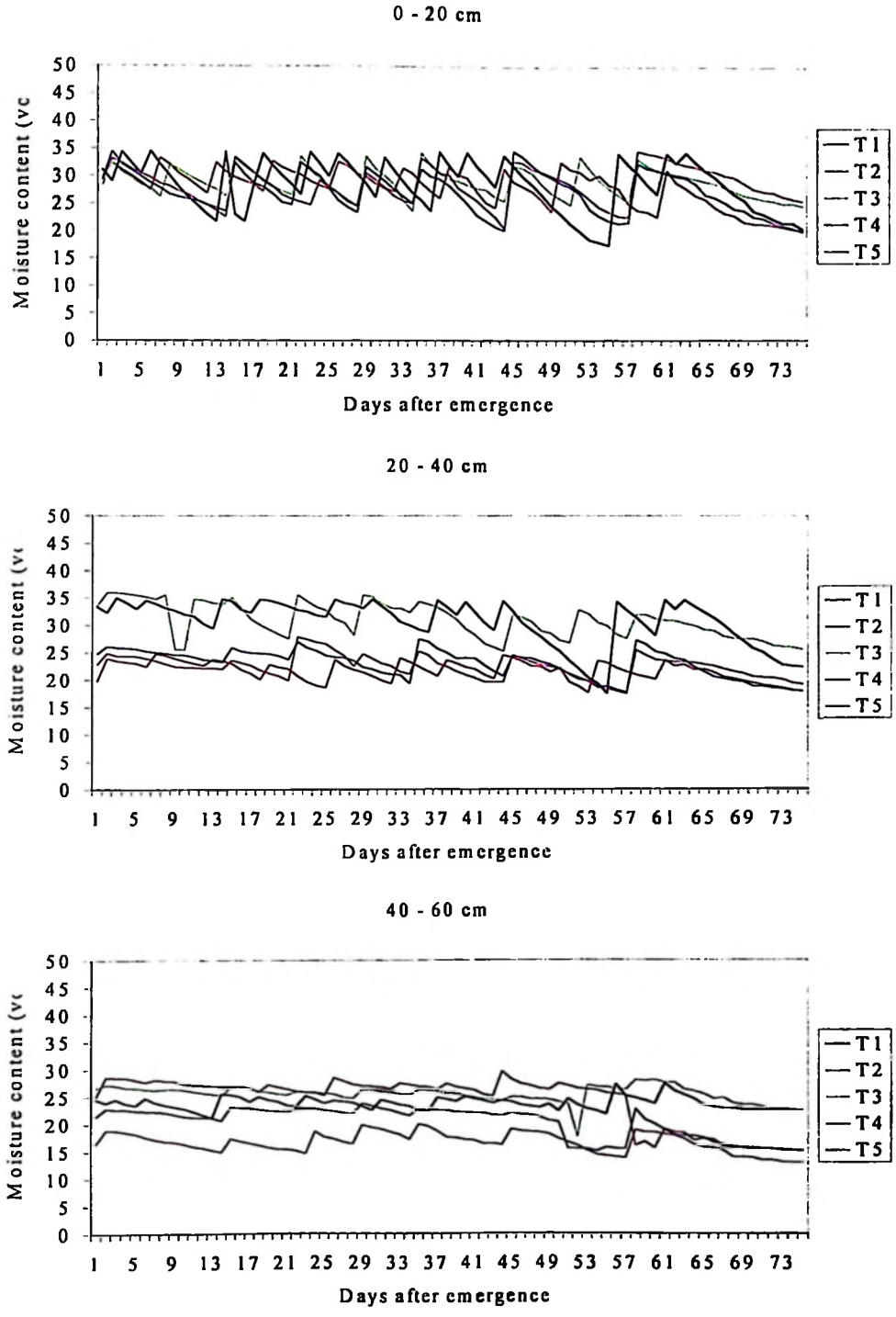

Figure 6: Soil moisture content for treatments in the Middle block

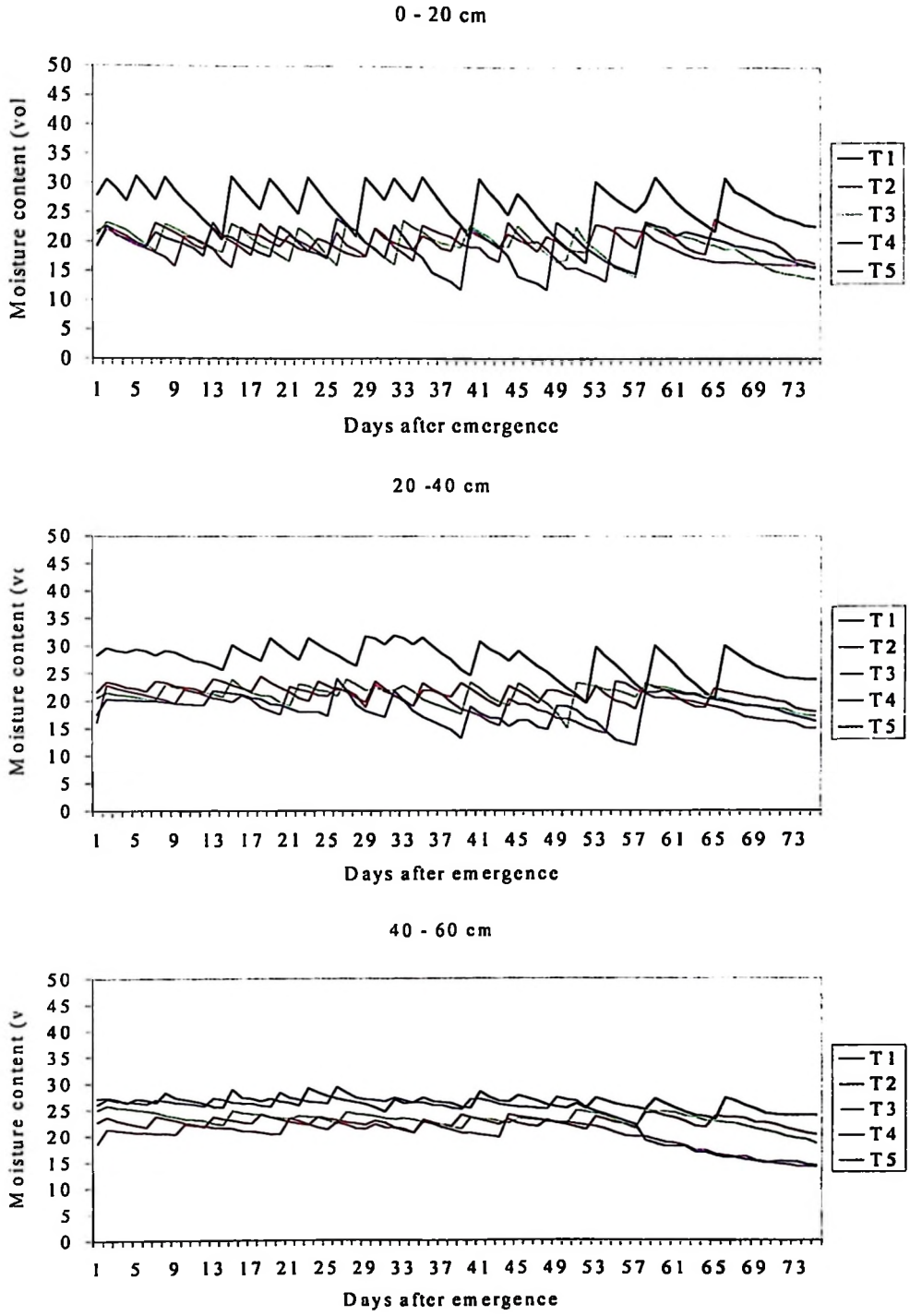

Figure 7: Soil moisture content for treatments in the Tail block

Figures 5, 6 and 7 show the soil moisture content in the 0-20, 20-40 and 40-60 cm depths for each treatment in the respective locations and offer an in-depth observation of the soil moisture content shown in Figure 8. Within the 0–40 cm depth there was high clay content for the soils in the Middle and Tail blocks as compared to those in the Head block. According to Ersahin and Brohi (in press), the spatial variability of soil properties may be random or systematic. A systematic variation has a consistent spatial pattern, which allows one to estimate a particular property at subjected locations. However, the soils in this study area showed a random variability of the soil properties thereby providing a challenge in generating uniform soil moisture content value for all locations.

Ersahin and Brohi (in press) found that among the soil properties that influence spatial variation in soil moisture content in the topsoil and sub-soil, the strongest influence is from soil texture, the more effective determinants being sand and silt. Since the knowledge of spatial variability of soil moisture content within a soil is important for managing soil moisture, the characterisation of soil moisture profiles along the crop root zone should be taken into account in modelling water budget of the root zone. The temporal soil moisture variation in the 20-60 cm depths ideally was dependent on the amount of irrigation water applied and on the contribution of soil moisture from the topsoil (Bertuzzi *et al.*, 1994; Reichardt *et al.*, 2001). That is why in some instances especially in the farmer managed treatment (T1) plot there were consistent changes in moisture content in the 20-60 cm depths as result of high irrigation water applications.

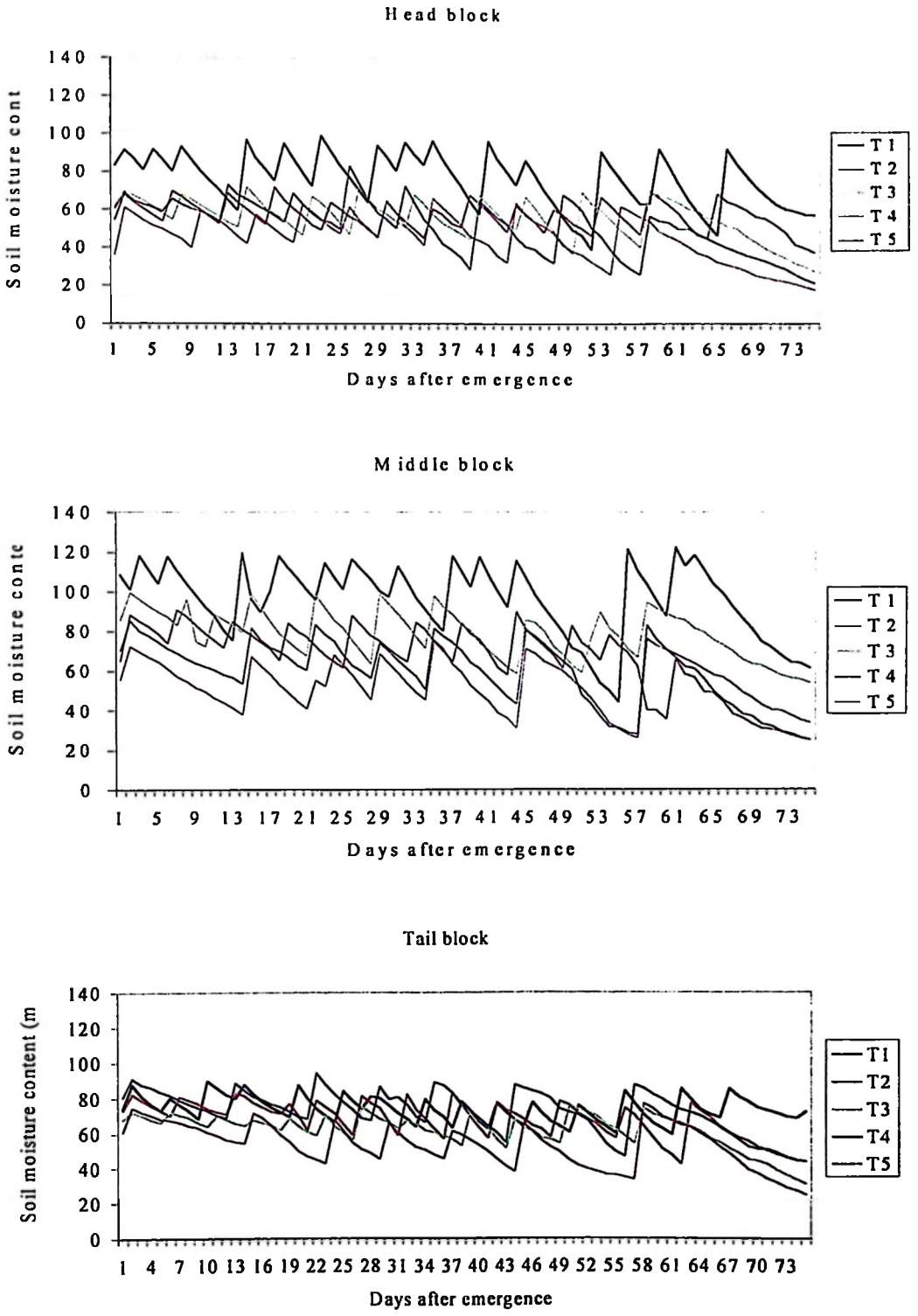

Figure 8: Root zone soil moisture content for respective treatments

At day one the soil moisture content could not be the same irrespective of the treatment because the soil in the study area was not homogeneous and soil moisture content in each treatment was measured from separate access tubes installed at the centre of each treatment plot as shown in Plate 2 and Plate 3. As a result, moisture contents at different treatment plots were variable on a particular day including after irrigation. Similar findings on variability in soil moisture content for a soil within a location were reported by Bertuzzi *et al.* (1994), Ersahin and Brohi (in press) and Reichardt *et al.* (2001). Variability in soil moisture content within an area presents practical difficulties in using average moisture content values to represent all points in the field during irrigation scheduling because eventually some points within the field will be over-irrigated while other points will be under-irrigated. As such, use of respective moisture content values for each point is essentially important to curtail such shortfalls.

The patterns of soil moisture content were more acute in the topsoil than in the subsoil as the soil moisture content continuously decreased until the next irrigation. The soil moisture content in the control and RDI treatments suggests that sufficient irrigation water was applied to replenish the root zone. Soil moisture content in the control and regulated deficit irrigation (RDI) treatments was replenished when the threshold water deficit was reached unlike in the farmer irrigated (T1) treatment. Irrigation water applications especially for the control and RDI treatments varied depending on the root zone depth used to schedule irrigations while in T1 treatment irrigation depths were under the farmers influence. The soil moisture content in T1 treatment after irrigation was higher than in the control and RDI treatments

indicating high and frequent irrigations by the farmers. Zhang et al. (2006) found similar results in spring wheat grown under regulated deficit irrigation in an arid area in China.

Higher frequency irrigations in T1 treatment created some favourable soil moisture conditions for bean growth and resulted in higher yields. Although the control was considered to be providing the most favourable soil moisture conditions, grain yields were lower than in T1 treatments. This could be because the soil moisture calculations in the RDI treatments were based on estimates with the neutron probe readings and not on the actual soil moisture contents.

4.2 Effects of RDI on water productivity

The physical water productivity (WP_{Y_IRR} and WP_{Y_ETa}) and combined physical and economic water productivity (WP_{GVP_IRR} and WP_{GVP_ETa}) with irrigation water applied and crop water use are presented in Figure 9 and Figure 10 respectively. The Head block had low water productivity values for the respective treatments.

The highest physical productivity of water with irrigation water applied was found in T4 treatment (1.27 kg/m^3) in the Middle block and in T3 treatment in the Head and Tail blocks, (0.81 kg/m^3 and 1.27 kg/m^3) respectively. The lowest physical productivity of water with irrigation water applied was found in T1 treatment in all locations in which the Head, Middle and Tail blocks had 0.21 kg/m^3, 0.58 kg/m^3 and 0.52 kg/m^3 respectively.

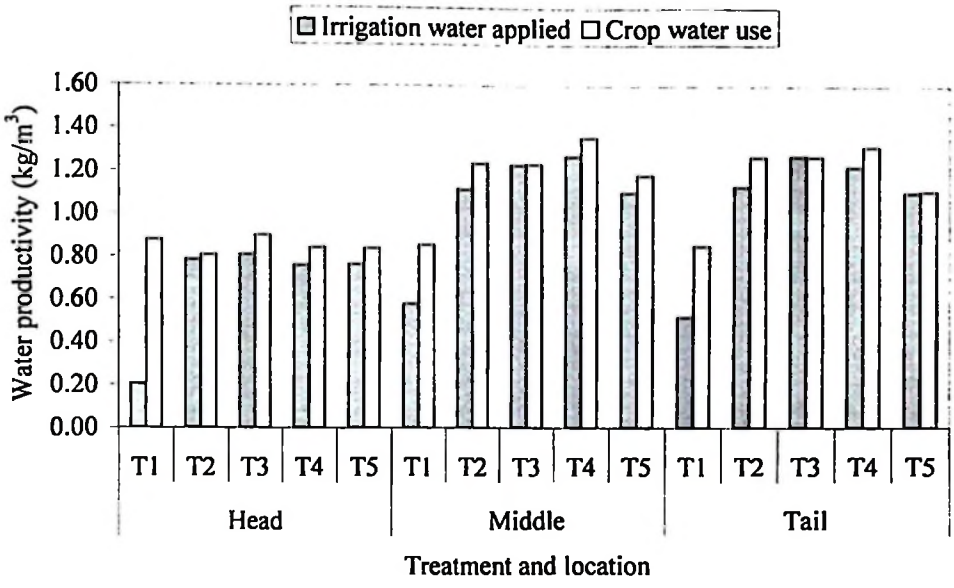

Figure 9: Physical productivity of water for the respective treatments

With crop water use, the highest physical productivity of water was found in T3 treatment (0.90 kg/m^3) in the Head block and in T4 treatment (1.36 kg/m^3 and 1.31 kg/m^3) in the Middle and Tail blocks respectively. The lowest physical productivity of water with crop water use was found in T2 treatment (0.81 kg/m^3) in the Head block and in T1 treatment (0.86 kg/m^3 and 0.85 kg/m^3) in the Middle and Tail blocks respectively.

The highest economic productivity of water with irrigation water applied was found in T4 treatment (Tsh 1014/m^3) in the Middle block and in T3 treatment in the Head and Tail blocks, (Tsh 647/m^3 and Tsh 1014/m^3) respectively. The lowest economic productivity of water with irrigation water applied was found in T1 treatment in all

locations in which the Head, Middle and Tail blocks had Tsh 165/m^3, Tsh 464/m^3 and Tsh 415/m^3 respectively.

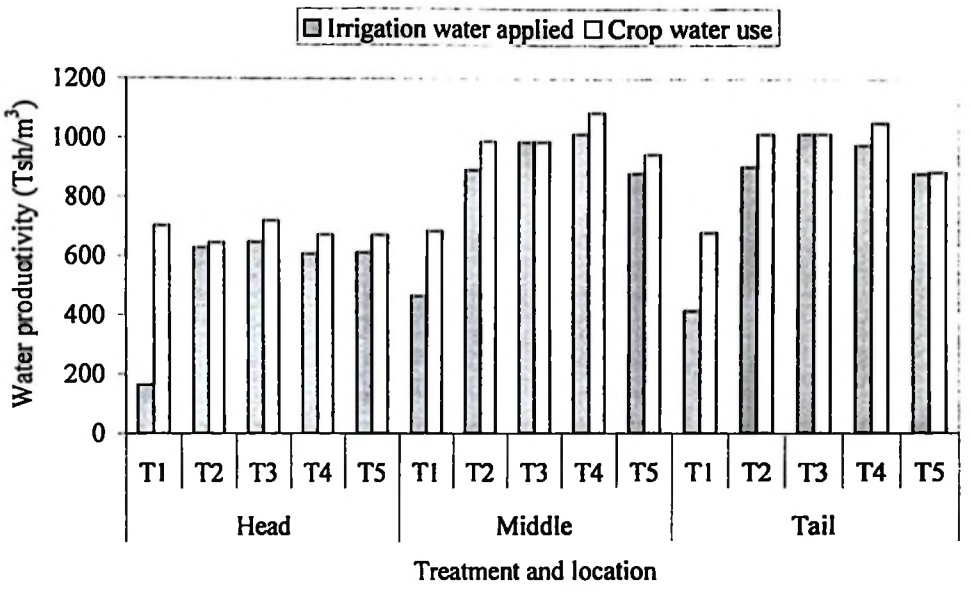

Figure 10: Economic productivity of water for the respective treatments

With crop water use, the highest economic productivity of water was found in T3 treatment (Tsh 720/m^3) in the Head block and in T4 treatment (Tsh 1085/m^3 and Tsh 1051/m^3) in the Middle and Tail blocks respectively. The lowest economic productivity of water with crop water use was found in T2 treatment (Tsh 645/m^3) in the Head block and in T1 treatment (Tsh 684/m^3 and Tsh 679/m^3) in the Middle and Tail blocks respectively.

Table 5 shows that there were no statistically significant differences in the productivity of irrigation water applied between T3 and T4, and between T2 and T5

treatments. The productivity of irrigation water applied in T1 treatment was significantly lower than the control and RDI treatments because the farmers over-irrigated their crops.

Table 5: Mean crop water use, irrigation, yield and water productivity

Treatment	Crop water use (mm)	Irrigation water applied (mm)	Yield (kg/ha)	WP_{Y_IRR} (kg/m^3)	WP_{GVP_IRR} (Tsh/m^3)
T1	315 ^{A}	735 ^{A}	2704 ^{A}	0.44 ^{C}	348 ^{C}
T2	232 ^{B}	252 ^{B}	2562 ^{AB}	1.01 ^{B}	807 ^{B}
T3	217 ^{BC}	225 ^{B}	2466 ^{B}	1.10 ^{A}	883 ^{A}
T4	191 ^{BC}	208 ^{B}	2233 ^{C}	1.08 ^{A}	866 ^{A}
T5	176 ^{C}	186 ^{C}	1835 ^{D}	0.99 ^{B}	791 ^{B}

Different letters within a column indicate significant difference at $P<0.05$

The irrigation depths in T1 treatment were, on average, two times higher as compared to the crop water use and were three times higher compared to irrigation depths in the control (T2) treatment. Shideed *et al.* (2003) also found that irrigation depths for wheat by smallholder farmers in Iraq were three times higher than the optimal amount recommended by research trials. Consequently, the productivity of water was reduced as most of the water applied was not productive enough as compared to what the crop used. This suggests that in T1 treatment there was wastage of water and that most of the irrigation water applied was lost as drainage water since irrigation depths were more than the crop water use. This shows that over-irrigation as well as higher water deficits can reduce the productivity of irrigation water in bean such that optimal amounts of water are required to maximise productivity of water.

4.2.1 Variability of water productivity due to RDI

The physical water productivity for harvested yield for dry beans can vary from 0.3 – 0.6 kg/m^3 (Doorenbos and Kassam, 1986). In the present study, physical water productivity for bean varied from 0.21 – 0.58 kg/m^3 in T1 treatment and from 0.76 – 1.27 kg/m^3 in the control and RDI treatments. Therefore, physical water productivity in the control and RDI treatments exceeded the range given by Doorenbos and Kassam (1986), a case similar to those reported in several other studies as shown in Table 6.

Table 6: Examples of reported water productivity of other crops

Crop	Water productivity (kg/m^3)		
	Minimum	Maximum	Doorenbos and Kassam (1986)
Wheat	0.11	2.67	0.8 – 1.0
Rice	0.46	2.20	0.7 – 1.1
Cotton	0.38	1.70	0.4 – 0.6
Maize	0.22	3.99	0.8 – 1.6

Source: Zwart and Bastiaanssen (2004)

Zwart and Bastiaanssen (2004) also reported that the water productivity was 0.6 – 1.7 kg/m^3 for wheat, 0.6 – 1.6 kg/m^3 for rice, 0.41 – 0.95 kg/m^3 for cotton and 1.1 – 2.7 kg/m^3 for maize. All these values were exceeding the range given by Doorenbos and Kassam (1986). The variability in water productivity occurred because data were collected in different environments (climatic locations), soils, irrigation and crop management, which affected not only the yield but also the crop water use, irrigation water diverted or supplied to the domain of interest (Zwart and Bastiaanssen, 2004).

Ahmad *et al.* (2004) also found that the water productivity for rice and wheat in Pakistan varied both spatially and temporally for sampled areas mainly due to differences in water use and soil quality among other factors. Although the data in the present study was collected in the same climatic location and crop management conditions, the results show that the level of performance through water productivity of the bean crop under RDI varied spatially for respective treatments. This provides a good assertion that RDI treatments of equal soil moisture depletion levels will produce different results under different locations; thus each location has an optimum level of RDI.

In their study, Ahmad *et al.* (2004) found that these spatial variability in water productivity under similar agro-climatic conditions are mainly attributed to access to irrigation water and differences in soil characteristics. The spatial variability in water productivity in the present study could also be attributed to the differences in soil among the locations and the differences in irrigation water applied to the respective treatments. There was variability in soil among the three locations especially within the 0-40 cm soil depth in which a greater concentration of roots are found for a bean crop. The soil in the Middle and Tail blocks had a greater proportion of clay within the 0-40 cm soil depth thereby possessing higher water holding capacity as compared to the Head block.

As a result, the soil in the Middle and Tail blocks provided ample moisture for crops than those in the Head block. The results suggests that crop production was maximised when RDI was scheduled at 50% soil moisture depletion in the Head

block and at 60% soil moisture depletion in the Middle and Tail blocks. Moreover, Table 5 show that the 50% soil moisture depletion would be the optimum level of stress that could be allowed under RDI in the scheme because statistically this level of stress produced the highest physical and economic productivity of water than the rest of the treatments.

4.2.2 Observed water productivity trend

Improvement in water productivities was observed in the control and RDI treatments as compared to the farmer irrigated treatment. Water productivity has been found to increase while simultaneously saving irrigation water through deficit irrigation than under full irrigation. However, maximum water productivity usually does not coincide with farmers' interests of maximising land productivity or economic profitability. Hence, farmers have a tendency to over-irrigate (Zwart and Bastiaanssen, 2004). For most cereal crops, yield is maximised at the account of water productivity (Perreira *et al.*, 2002). Therefore, when water is a limiting resource to production, maximising water productivity may be more profitable to a farmer than maximising crop yield because the water saved becomes available to irrigate more land.

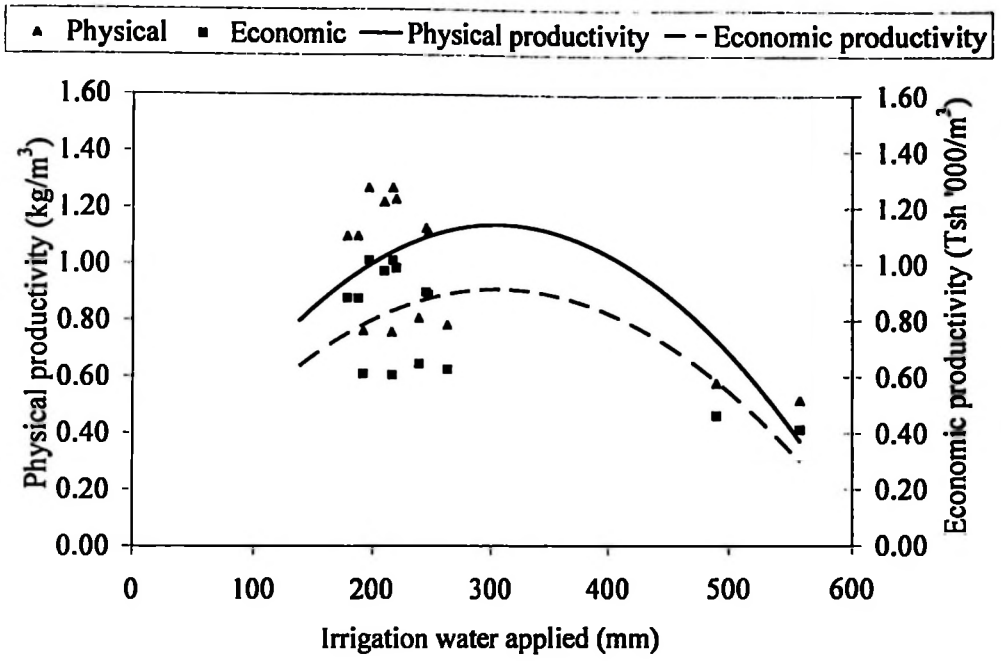

Figure 11: Observed water productivity trend for the study

Figure 11 shows that, on average, higher irrigation water productivities were found at irrigation depths that were lower than irrigation depths for maximum yield. Zhang (2003), Bouman and Tuong (2001), Nautiyal *et al.* (1999) and El Amami *et al.* (2001) in their irrigation studies involving different irrigation levels also found that deficit irrigation had higher productivity of irrigation water applied than full irrigation. However, too low irrigation water depths that were considered adverse resulted in low water productivities. The present study also found that too high (T1 treatment) and too low (T5 treatment) irrigation depths produced lower water productivities.

4.2.3 Improvement in water productivity with RDI

The improvement in water productivity under RDI treatments compared to T1 treatment suggests that there is scope for increasing water productivity with respect to depleted water by adopting RDI strategy in bean production in the scheme. As such, a shift in irrigation water management may be required in the scheme to move away from 'maximum irrigation-maximum yield' strategies to 'less irrigation-maximum water productivity' strategies. However, to achieve this strategy, moderate water deficits during the vegetative stages would be appropriate under RDI because higher water deficits as in T5 treatment tend to reduce water productivity. In crops such as wheat and sorghum, Pandey *et al.* (2000), Zhang (2002), Romero *et al.* (2004) and Lamm *et al.* (1994) also found that water productivity was significantly low because of severe irrigation water deficits.

On the other hand, apart from improvement in water productivity with deficit irrigation alone, high yielding varieties and agronomic manipulation also improve water productivity for a crop as has been reported for a rice crop under deficit irrigation (Tuong and Bhuiyan, 1999). The improvement in water productivity under the control and RDI treatments in this study could also be attributed to improvement in the crop used as it was a high yielding variety (Madata, 2004). The bean variety used in this study was harvested 77 days after germination while most bean varieties take 90-120 days (Doorenbos and Kassam, 1984). The early maturing and high yielding varieties improve water productivity by increasing yield and reducing crop duration and seasonal crop water use. By increasing yield together with the reduction in crop growth and duration and hence seasonal crop water use, the modern varieties

have about a threefold increase in water productivity compared with the traditional varieties (Barker *et al.*, 2003; Kijne *et al.*, 2003).

The positive water productivity trend found in this study shows that it is feasible to adopt RDI strategy because reducing irrigation depths increased the returns per unit volume of water. However, there are exceptions in which severe water deficits would not be feasible because the returns per unit volume of water decrease considerably, as found in T4 and T5 treatments. Dichio *et al.* (2004), Lamm *et al.* (1994), Martin *et al.* (1991) and Sarwar and Perry (2002) also found the 50-60% soil moisture depletion level to be the critical water deficit range under which deficit irrigation improved water productivity with acceptable yield in vineyard.

4.3 Irrigation water savings

Irrigation water savings and reductions in grain yield from respective irrigation options compared to the control are presented in Figure 12. There was an increase in water savings under RDI that was associated with reduction in grain yield. Higher yield reductions were found in the Head block than in the Middle and Tail blocks for respective irrigation options. Yield reductions were directly influenced by irrigation water savings such that greater water savings resulted in greater yield reduction.

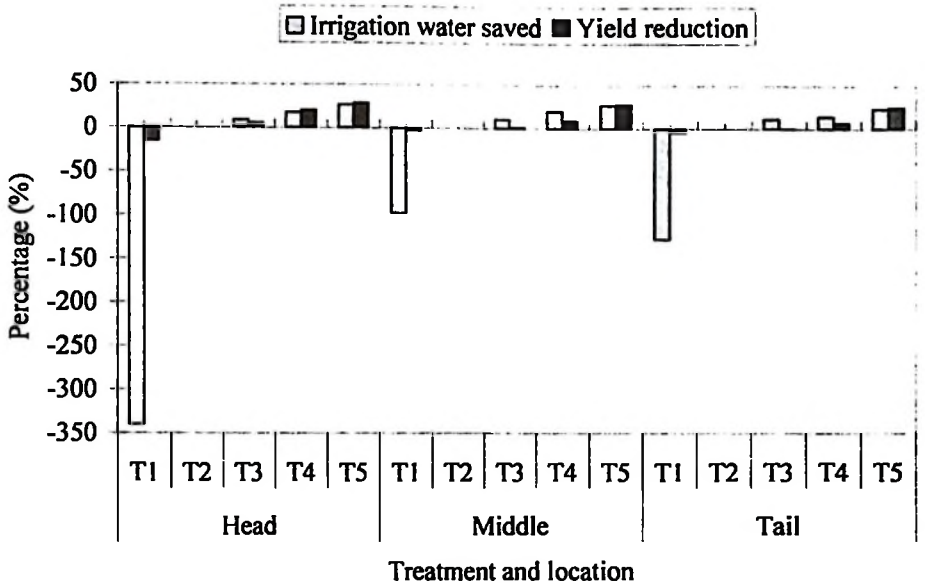

Figure 12: Irrigation water saved and yield reduction

Irrigation water saved under RDI varied from 9 to 28% while yield reduction varied from 0 to 29%. Yields were not significantly reduced by saving 10% of irrigation water in T3 treatment. Significant 12% and 29% yield reduction was found in T4 and T5 treatments by saving 17% and 28% irrigation water respectively. English (1990) and Lamm *et al.* (1994) also found that wheat and maize yields were reduced when deficit irrigation was scheduled beyond the 50% soil moisture depletion. In perennial crops, Kriedemann and Goodwin (2004), Gonzalez and Castel (2004), Romero *et al.* (2003), Goldhamer (2000), English (1990) and Pandey *et al.* (2000) found that 6 to 30% irrigation water was saved under RDI without significant yield reduction. This shows that there is variability for water that can be saved for different crops and environments without significant yield reductions.

Table 7: Mean irrigation water saved and yield reduction

Treatment	Number of irrigations	Water saved (%)	Yield reduction (%)
T1	16	-189	-8
T2	12	-	-
T3	10	10	3
T4	8	17	12
T5	6	26	27

For different RDI treatments, the irrigation frequency for the growing season was variable as shown in Table 7. Therefore, the net water use was different because of differences in deficit levels subjected to the treatments. The crop water use varied from 167-256 mm for the RDI treatments while in the farmer managed treatment the crop water use varied between 272-340 mm. The rationale behind RDI is minimisation rather than maximisation of seasonal crop water use (Kriedemann and Goodwin, 2004; Moutonnet, 2004). Similarly, Kashyap and Panda (2003) found that on the same soil in India, the seasonal crop water use for potato crop under deficit irrigation varied between 164-208 mm when soil moisture depletion was varied between 10–75%. The lowest values were found in the high soil moisture depletion treatments. Sezen *et al.* (2005) found that the seasonal crop water use for green beans varied between 253-338 mm for different treatments in Turkey. Zhang *et al.* (2004) found that wheat crop water use under different irrigation schedules in a loam soil in North China Plain varied between 209-457 mm with a significant reduction under severe soil moisture deficit.

Table 7 shows that reductions in grain yield were highest in T5 treatment due to high irrigation water savings. However, by imposing moderate 50% soil moisture

depletion level (T3 treatment) water savings were higher with low yield reductions. Wample and Smithyman (2002) and Adiku *et al.* (2001) also found that the only attributable expense of using RDI as a water management strategy is a potential loss of yield if stress becomes excessive.

This suggests further that the 50% soil moisture depletion is the optimum deficit level at which RDI could be practiced in the Herman irrigation scheme without significant yield reductions. Therefore, farmers in this scheme could reduce their irrigation depths without significant yield loss. However, for RDI to be successful, farmers need to know the deficit that can be allowed at each of the growth stages, the level of water stress that already exists in the root zone and, most importantly, have control over the timing and amount of irrigations.

The critical constraint faced by most farmers is their inability to determine and apply correct amounts of crop water demand at specific times during the crop growth period (Burton *et al.*, 1999). Irrigation applications by farmers in this study were two times higher than the crop water use and three times higher compared to the control treatment. The farmers irrigated without prior determination of crop water demand as compared to the irrigation strategy employed in the control and RDI treatments.

Consequently, more water was applied in the farmer-managed irrigation compared to the control and RDI treatments leading to water wastage. In traditional irrigation schemes, the practice of cutting off the supply when the advance is complete induces large variations in applied water volumes at each irrigation event and from one field

to the next that often results in over-irrigation (Perreira *et al.*, 2002). In many situations, farmers have little incentive to conserve water and thus retard innovations for water saving technologies (Yang *et al.*, 2003).

4.4 Effect of water deficits on crop water use

Figure 13 shows the crop water use during pre-flowering (PRF), flowering and pod filling (FPF) and post-flowering (POF) stages for the respective treatments. In all the locations, T1 treatment had the highest crop water use during all the three growth periods except during the POF stage in the Head block. There were spatial variations in crop water use among the control and RDI treatments. However, T5 treatment had the lowest crop water use in all locations and growth stages except in Tail block during the PRF stage.

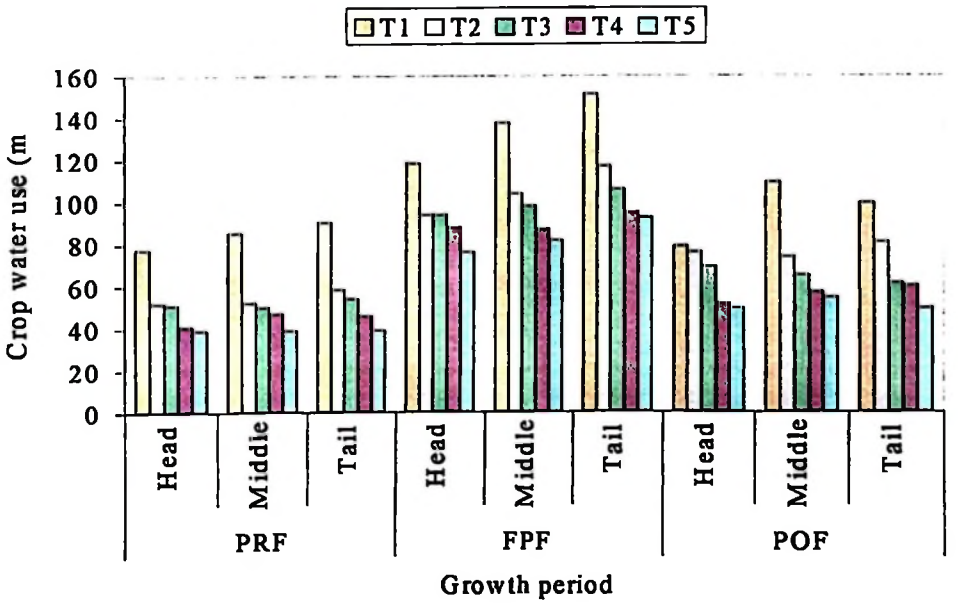

Figure 13: Crop water use in respective treatments in specific growth stages

The crop water use was significantly highest in T1 treatment than the RDI treatments during all growth stages except during POF stage in the Head block as shown in Table 8. There were no significant differences in crop water use during the PRF stage among the control and RDI treatments. However, during FPF and POF stages, crop water use in T5 treatment was significantly lower as compared to the control and other RDI treatments. During the same period, no significant differences in crop water use among the control, T3 and T4 treatments were observed. This suggests that crops in T5 treatment were subjected to severe moisture deficit during PRF stage and could not fully recover from the moisture deficit during that stage to increase crop water use as compared to T3 and T4 treatments.

Although the level of soil moisture depletion was the same for all treatments during the Flowering and Pod Filling stage, the differences in crop water use among the treatments were influenced by the spatial variability in soil within the blocks. Soil spatial variability, as is dominantly influenced by the sand and silt particles, generates differences in available soil moisture and hence crop water use (Ersahin and Brohi, in press; Reichardt *et al.*, 2001). On the other hand, heavily stressed RDI treatments showed an impaired ability in crop water use to recur from the stress imposed during the early vegetative stage.

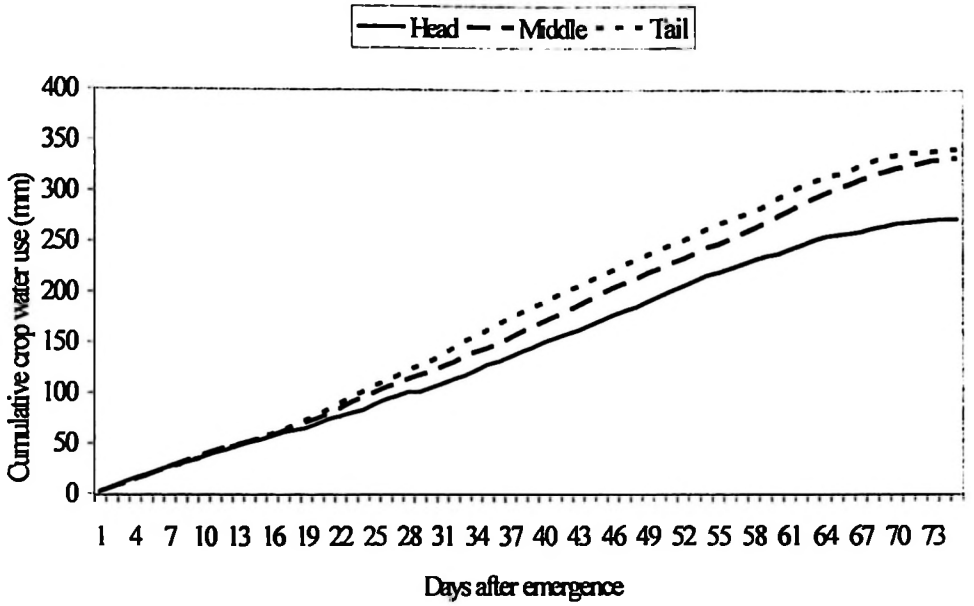

Figure 14: Cumulative crop water use in T1 treatment

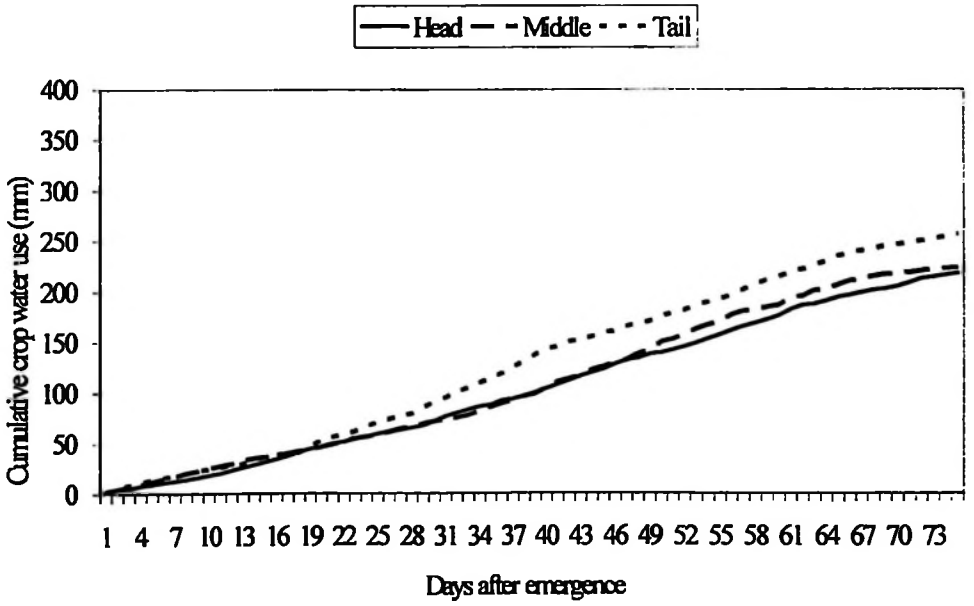

Figure 15: Cumulative crop water use in T2 treatment

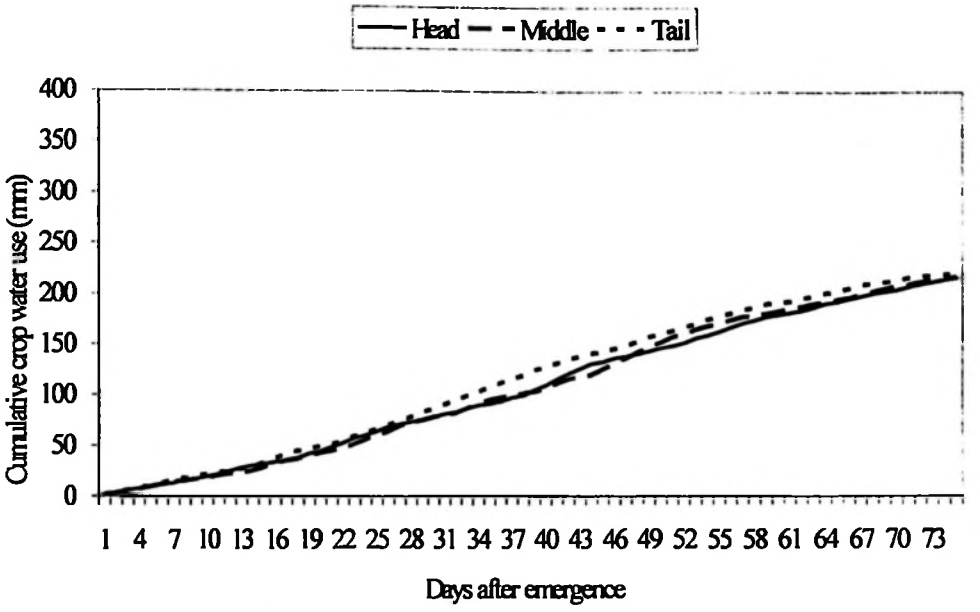

Figure 16: Cumulative crop water use in T3 treatment

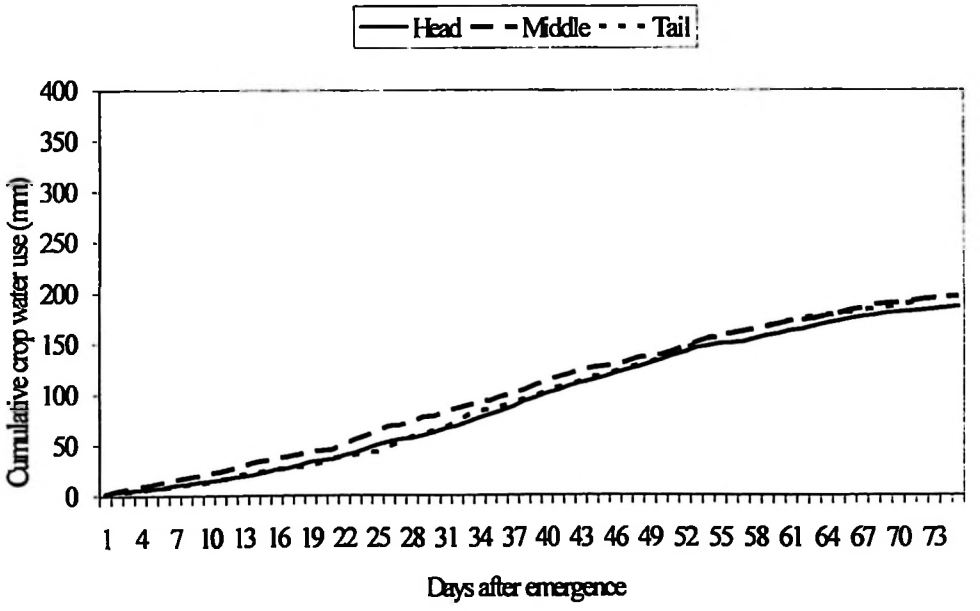

Figure 17: Cumulative crop water use in T4 treatment

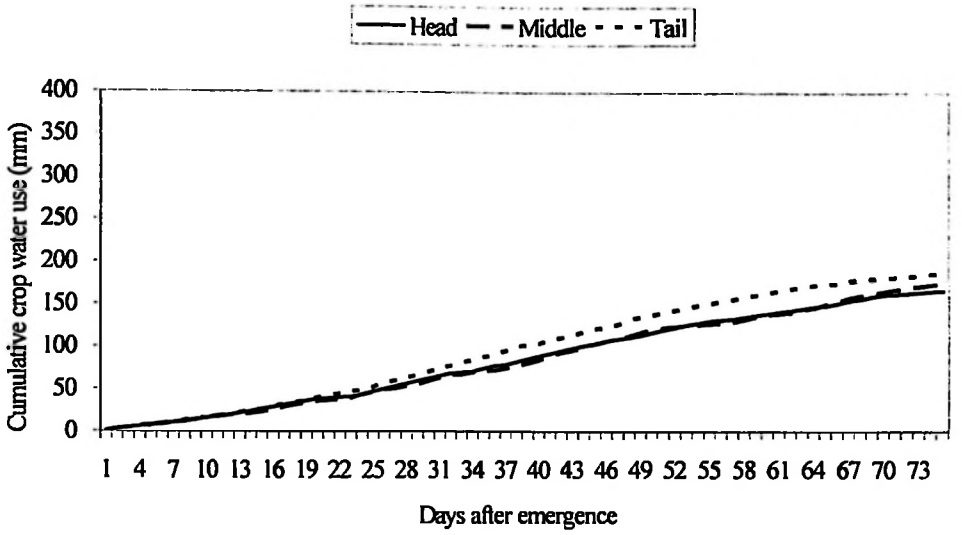

Figure 18: Cumulative crop water use in T5 treatment

The cumulative crop water use shown in Figures 14, 15, 16, 17 and 18 suggests that the low crop water use in T5 treatments could be attributed to poor root system due to severe water stress during the PRF stage as compared to the moderate water stress in T3 treatment. Nielsen and Nelson (1998) also found that soil water extraction in bean was reduced due to water stress. The reduction in crop water use was possibly a result of the leaf area reduction, or restricted root development due to water stress during the vegetative stage. According to Bertuzzi *et al.* (1994) and Eghball *et al.* (1993), root system development is an important factor for rapid soil moisture absorption by a crop such that when water stress is severe, the root system is damaged and results in fewer roots branching which would imply an impaired ability for the crop to take up water. Therefore, the crop water use patterns within the growth stage were an indication of root activity.

Table 8: Mean crop water use (mm) at different growth periods

Treatment	Growth period		
	Pre-flowering	Flowering and Pod Filling	Post-Flowering
T1	84 ^{A}	136 ^{A}	95 ^{A}
T2	54 ^{B}	103 ^{B}	79 ^{B}
T3	50 ^{B}	102 ^{B}	65 ^{BC}
T4	46 ^{B}	99 ^{B}	65 ^{BC}
T5	43 ^{B}	91 ^{C}	55 ^{C}

Different letters within a column indicate significant difference at $P<0.05$

Bertuzzi *et al.* (1994) found that spatial variability in soil can lead to variability in crop water use. In this study, the spatial variability in soil within the 0–40cm soil layer for the three blocks could have contributed to the spatial variability in crop water use. Moreover, Nielson and Nelson (1998) found that soil water extraction by a bean crop was significantly different only in the topsoil layer (0–30cm) than the other underlying root zone layers where soil water extraction was practically the same.

The water holding capacity within the 0–40cm depth was higher in the Middle and Tail blocks compared to the Head block. Since about 60% of soil moisture extraction for bean crop occurs within the top 30cm of the root zone due to high root concentration in that region, crop water use for similar treatments was higher where water holding capacity was also high although the level of deficit was similar. The water holding capacity for the three blocks was based on estimates from the neutron probe field capacity measurements and soil analysis. However, Reichardt *et al.* (2001) found that the only practical way of irrigation is the use of an average water depth, due to the inherent variability of the soil, and that the search for better field

capacity values does not imply better water depth estimates. Soil spatial variability of physical properties is a complication for irrigation management accomplishment. However, to establish average water depths for an entire field has been found that in any case spots of the field will have excess and others deficit of water after an irrigation that is considered homogenous.

Since the calculation of the irrigation water depth involves knowledge of the actual soil water content before irrigation, of the soil water content at field capacity, and of soil bulk density, it is obvious that in this study the estimation of these properties for the respective treatments among the blocks contributed to the variation in crop water use patterns because of either over-estimation or under-estimation.

4.5 Sensitivity of RDI on beans yield

The yield response factor, λ_y, was determined for the bean crop taking into consideration all the data in the different blocks. The maximum yield (Y_m), actual yield (Y_a), maximum crop water use (ET_m) and actual crop water use (ET_a) presented in Table 9 were used to determine the relative yield decrease ($1 - Y_a/Y_m$) and relative evapotranspiration deficit ($1 - ET_a/ET_m$).

The linear relationship between relative yield decrease and relative evaptranspiration deficit is shown in Figures 19, 20 and 21.

Table 9: Yield and crop water use for the respective treatments

Block	Treatment	Y_m (kg/ha)	Y_a (kg/ha)	ET_m (mm)	ET_a (mm)
Head	T1	2387		272	
	T2		2064		256
	T3		1934		215
	T4		1640		195
	T5		1468		175
Middle	T1	2839		332	
	T2		2754		223
	T3		2712		220
	T4		2496		184
	T5		1970		167
Tail	T1	2886		340	
	T2		2761		218
	T3		2751		217
	T4		2526		195
	T5		2067		187

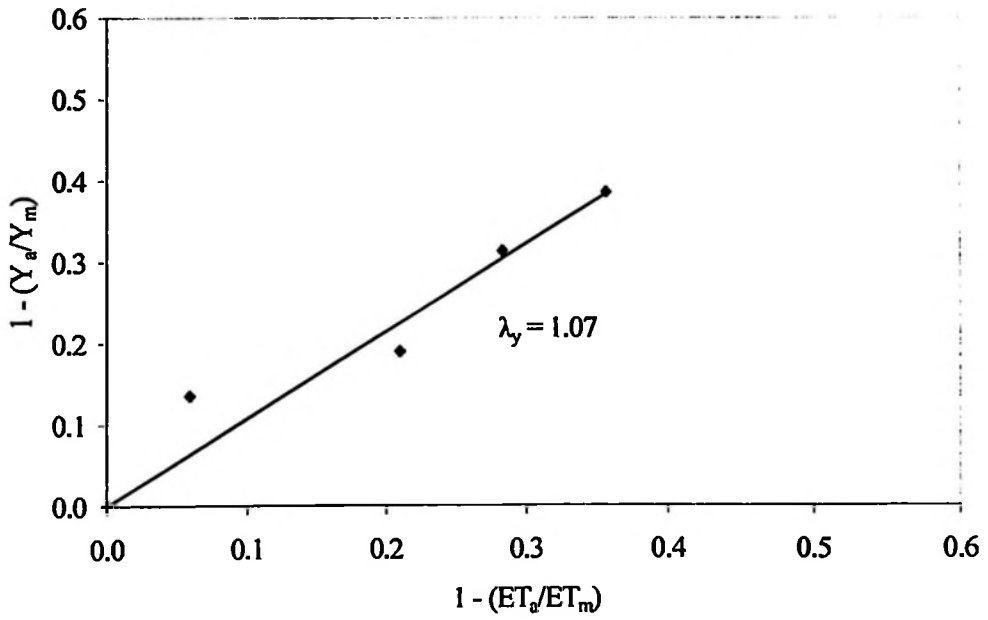

Figure 19: Yield response factor in the Head block

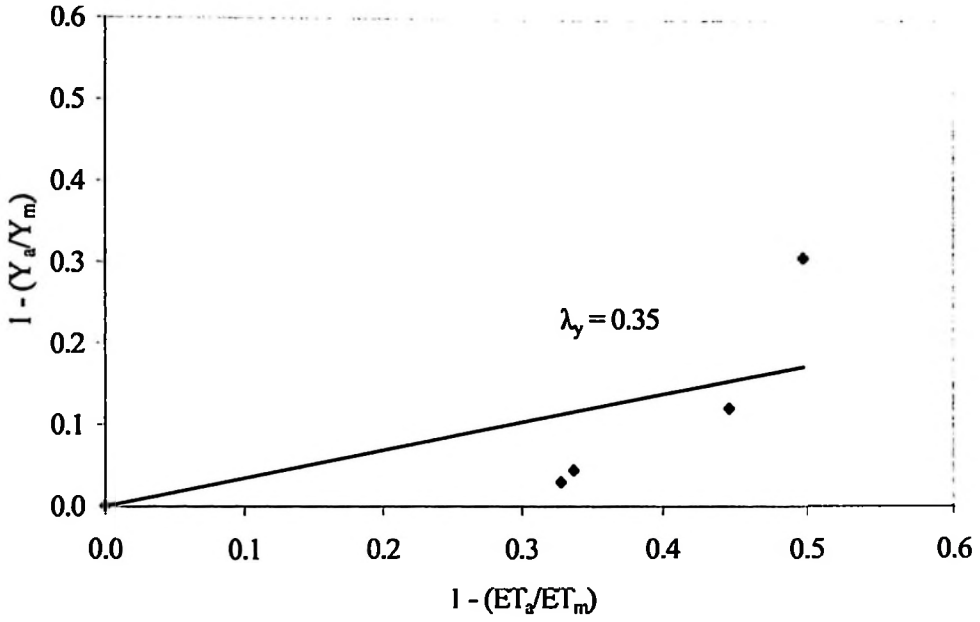

Figure 20: Yield response factor in the Middle block

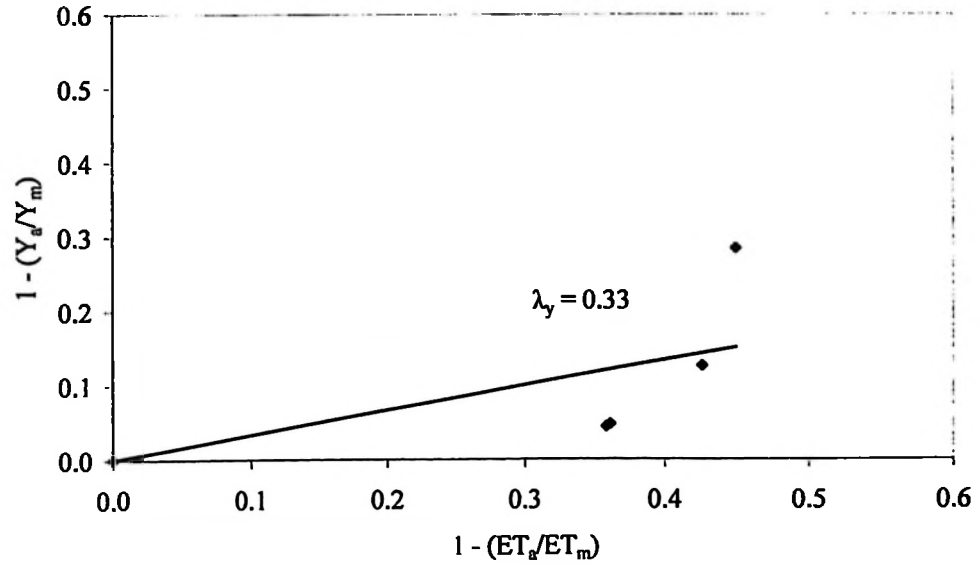

Figure 21: Yield response factor in the Tail block

The yield response factor was 1.07, 0.35 and 0.33 in the Head, Middle and Tail blocks respectively. When combined values for the three locations were used, the yield response factor was 0.50. Different studies found variable yield response factors for a bean crop for the whole growing season. For example, the yield response factor for beans was 1.23 in Turkey (Sezen *et al.*, 2005), 0.99 in Turkey (Kirda, 1999) and 0.59 in Brazil (Moutonnet, 2002). However, Doorenbos and Kassam (1986) give a value of 1.15 for the whole growing season. This suggests that the bean crop was very sensitive to regulated deficit irrigation in the Head block than the rest of the blocks and this sensitivity was also reflected in the yield and yield components as shown in Section 4.6. The yield response factor for the whole scheme suggests that the bean crop was not very sensitive to regulated deficit irrigation.

4.6 Sensitivity on yield and yield components

The sensitivity of water stress is complex and highly variable due to interacting factors. The variability in yield of a crop can be related to variability in yield components as yield depends on the development of these components (Boutraa and Sanders, 2001; Dapaah *et al.*, 1999). The expressions of most traits of common bean are reduced under water stress conditions and the effects of water stress on the yield and yield components can be highly significant (Boutraa and Sanders, 2001). In the present study, grain yield, 100 seeds weight, seeds per pod and pods per plant were the yield and yield components that were used to assess the sensitivity of the respective irrigation options.

4.6.1 Pods per plant

The number of pods per plant in each treatment is presented in Figure 22. There were no significant differences in number of pods per plant among T1, T2 and T3 treatments as shown in Table 10 although the number of pods per plant was lowest in the Head block. However, water stress during pre-flowering and post-flowering stages in T4 and T5 treatments significantly reduced the number of pods per plant as a bean yield component.

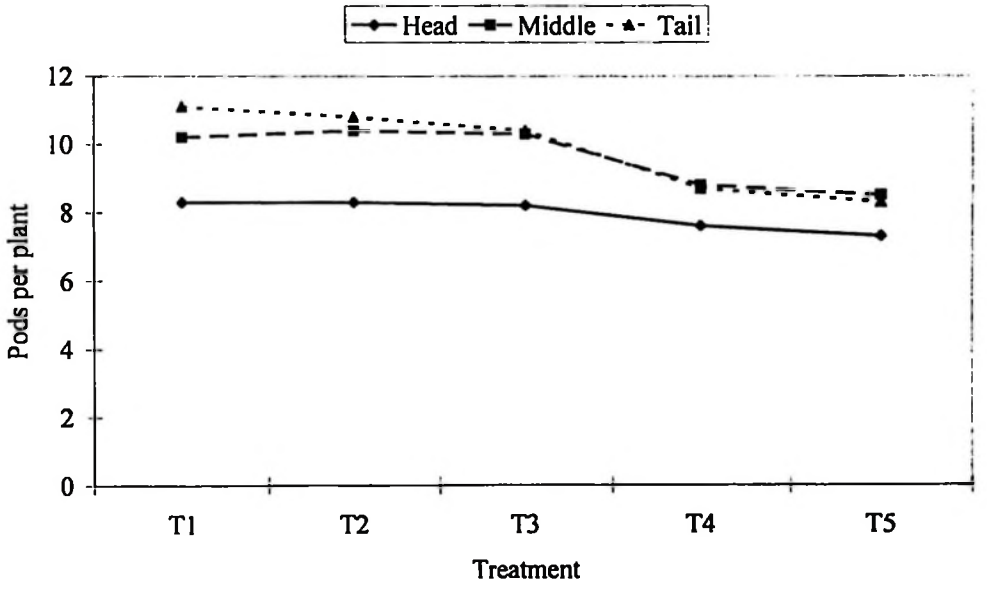

Figure 22: Number of pods per plant for the respective treatments

The Head block produced the least number of pods per plant when there was easy access to irrigation water. This might have been influenced by the differences in soil among the locations. Within each block the highest number of pods per plant was found in the farmer managed treatment in which irrigation water applied was higher

than the RDI treatments as shown in Figure 22. However, soil in the Head block possessed limited crop available soil moisture than those in the Middle and Tail blocks. Available soil moisture controls crop growth and influences a variety of soil processes including chemical exchange, transport of solutes and energy balance of the soil-crop system (Ersahin and Brohi, in press). Therefore, the soil variability played a significant influence on the number of pods per plant among locations consequently the Head block produced the least number of pods per plant.

Dapaah *et al.* (1999) also found an increase in the number of pods per plant due to irrigation. Several other researchers such as Musallam *et al.* (2004), Singh (1995), Nielsen and Nelson (1998), Calvache *et al.* (1997), Boutraa and Sanders (2001), Onder *et al.* (2006) and Barrios *et al.* (2005) also reported that the number of pods per plant seems to be the yield component that is most affected by water stress and can reduce grain yield up to 70% depending on the duration and intensity of stress period.

4.6.2 Seeds per pods

The number of seeds per pod in each treatment is presented in Figure 23. The number of seeds per pod was not significantly affected by irrigation water as shown in Table 10.

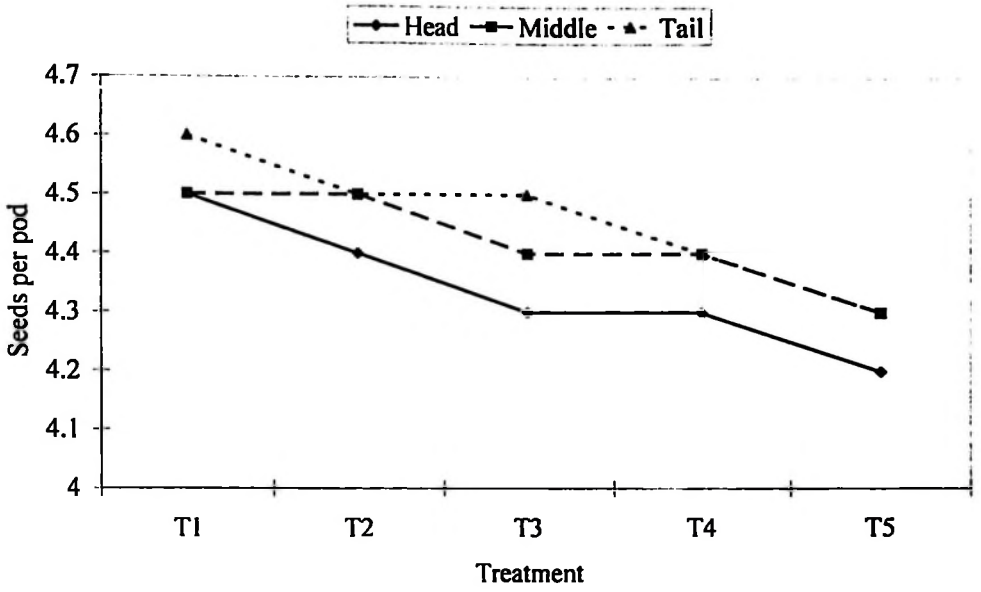

Figure 23: Number of seeds per pod for the respective treatments

Other researchers such as Romero *et al.* (2004), Mussallam *et al.* (2004), Boutraa and Sanders (2001), and Barrios *et al.* (2005) also found that the number of seeds per pod is a stable yield component that is not significantly reduced by water stress. However, Dapaah *et al.* (1999) found an increase in the number of seeds per pod with irrigation. Similarly, Calvache *et al.* (1997) found that deficit irrigation reduced the number of seeds per pod in beans.

4.6.3 One hundred (100) seeds weight

The 100 seeds weight in each treatment is presented in Figure 24. There were no significant differences in 100 seeds weight among the control, T1 and T3 treatments as shown in Table 10.

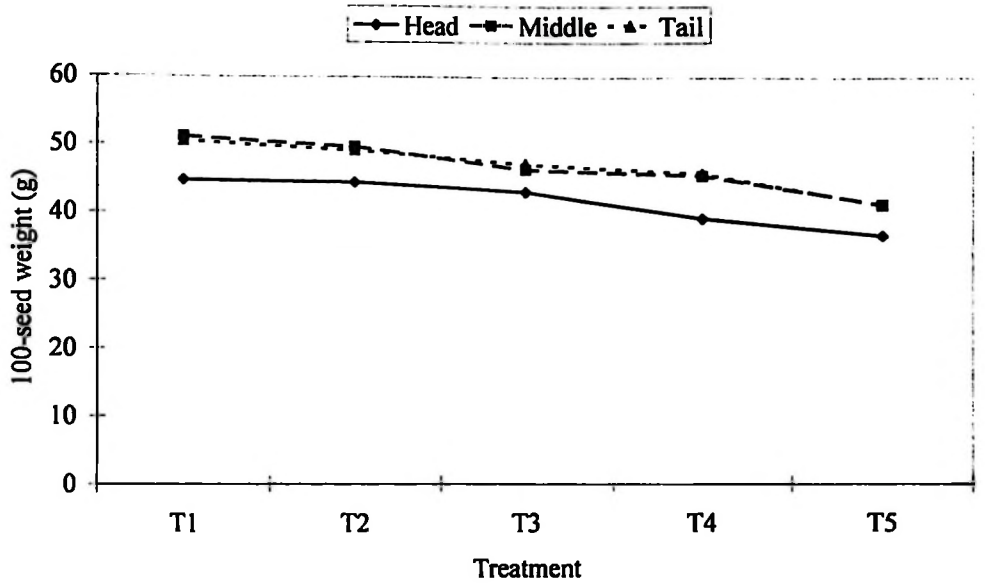

Figure 24: Weight of 100 seeds for the respective treatments

The 100 seeds weight in T4 and T5 treatments were significantly lower compared to the control treatment. Singh *et al.* (1987), Nielsen and Nelson (1998) and Calvache *et al.* (1997) also found that severe water deficit in bean crop reduced the mean 100 seeds weight. Zhang *et al.* (2002) reported that severe soil water deficit in wheat significantly reduced 1000-kernel weight and grain yield.

4.6.4 Grain yield

The grain yield in each treatment is presented in Figure 25. There were no significant differences in yield among the control, T1 and T3 treatments as shown in Table 10. However, yield in T4 and T5 treatments were significantly lower compared to the control treatment. Grain yield was highest in T1 treatment and lowest in T5 treatment.

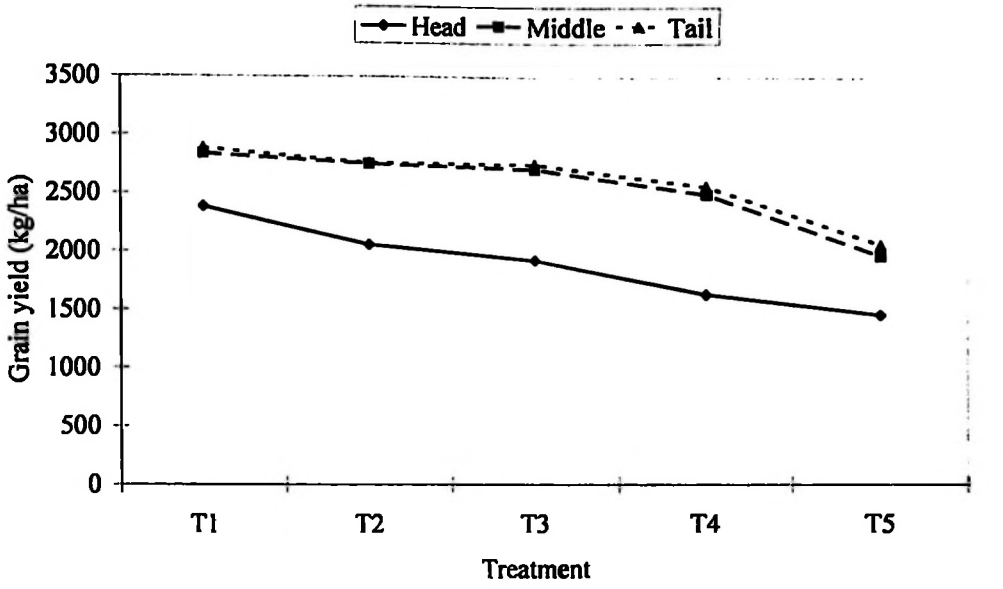

Figure 25: Grain yield for the respective treatments

Singh *et al.* (1987) and Mussallam *et al.* (2004) also found significant reduction in bean yield due to excessive water deficits and the reduction was severe when water stress was imposed during flowering than vegetative period. Zhang *et al.* (2006) found that wheat grain yield and most of its components were not significantly reduced by RDI but greatly improved except for the 1000 seeds weight as compared to the water stress free treatment.

Barrios *et al.* (2005) reported that bean yield was reduced by 25.7% when the number of pods per plant was highly affected by water stress. The number of pods per plant was reduced by 63.3% as compared to 28.9% and 22.3% reduction in number of seeds per pod and 100 seeds weight, respectively. The decrease in yield of many grain legumes grown under water stress is largely due to the reduction in the

number of pods per plant (Barrios *et al.*, 2005). However, when soil moisture reaches the lower levels of available soil moisture, the weight of individual seeds and the number of seeds per pod may play an important role in determining the final yield.

Table 10: Mean yield and yield components

Treatment	Pods per plant	Seeds per pod	100 seeds (g)	Yield (kg/ha)
T1	9.9 ^{A}	4.5 ^{A}	48.9 ^{A}	2704.0 ^{A}
T2	9.8 ^{A}	4.5 ^{A}	47.8 ^{A}	2526.3 ^{AB}
T3	9.6 ^{A}	4.4 ^{A}	45.6 ^{AB}	2465.7 ^{B}
T4	8.4 ^{B}	4.4 ^{A}	43.5 ^{BC}	2232.7 ^{C}
T5	8.0 ^{B}	4.3 ^{A}	39.7 ^{C}	1835.0 ^{D}

Different letters within a column indicate significant difference at $P<0.05$

Table 10 indicates that statistically there were significant differences in yield and yield components among the respective treatments except for the number of seeds per pod. The number of seeds per pod was found to be a stable yield component not affected by water deficits.

4.6.5 Relationship between grain yield and yield components

The correlation coefficients between grain yield and yield components is presented in Table 11. Higher correlation ($r = 0.95$) was found between 100 seeds weight and grain yield. The correlation coefficients show that the 100 seeds weight was the only yield component that was highly correlated to grain yield. The number of seeds per pod had the lowest correlation coefficient indicating that this yield component does not have a greater influence on yield. Therefore, the positive relationship between grain yield and 100 seeds weight might indicate the importance of seed weight in determining the final yield of bean especially under soil moisture deficits.

Table 11: Correlation coefficients between grain yield and yield components

	Seeds per pod	Pods per plant	Yield (kg/ha)
100 seeds (g)	0.92	0.90	0.95
Seeds per pod	-	0.83	0.89
Pods per plant	-	-	0.91

Most studies have found the number of pods per plant and 100 seeds weight as the yield components that have the highest positive correlation to grain yield in beans (Pilbeam *et al.*, 1992). For example, Musallam *et al.* (2004) found positive significant correlation (r = 0.709) between grain yield and 100 seeds weight. Dapaah *et al.* (1999) also found that 100 seeds weight and the number of pods per plant were the yield components most highly correlated with grain yield. The only stable yield component was the number of seeds per pod that did not show any significant effect due to water stress.

The yield components in each treatment were lower in the Head block than in the Middle and Tail blocks. Similarly, Musallam *et al.* (2004) reported that there were highly significant location effects for all yield components except for number of seeds per pod. Therefore, yield performance of bean depends also on the environmental conditions in which it is growing.

4.6.6 Factors contributing to yield variability

There are many reports of grain yield reduction due to water deficits in bean. When soil moisture reaches the lower values of available moisture the number of seeds per pod and seed weight may play an important role in diminishing grain yield. Nielsen and Nelson (1998) and Calvache *et al.* (1997) found that bean yield was reduced

because of a reduction in the number of pods per plant and 100 seeds weight. The decrease in bean yields under water stress conditions in the present study are largely due to the reduction in number of pods per plant and 100 seeds weight. Higher soil moisture deficits significantly reduced grain yield in T4 and T5 treatments by reducing the number of pods per plant and 100 seeds weight, the yield components that are highly correlated with grain yield. These results agree with those reported by Dapaah *et al.* (1999) and Pilbeam (1992).

The increase in bean yield is associated with the removal of moisture stress at particular phases in the growth of the bean plant (Blum, 2004). Moreover, Arora and Gajri (2000) found that there is a direct and proportional gross reduction in assimilates partitioning to pods due to the degree of water stress. Therefore, high water deficits during the post-flowering stage inT4 and T5 treatments were responsible for the significant loss in yield since the number of pods per plant and 100 seeds weight were reduced under these treatments.

According to Sprent *et al.* (1977), cited by Musallam *et al.* (2004), water supply may be a more important factor, than either solar radiation or plant competition, in controlling yield, especially for the period following pod setting when the plant water requirements become high. The grain yield in this study was high in T1 treatment in which no moisture stress was imposed at any growth period. Although soil moisture deficit was imposed during the vegetative stages in T3 treatment, grain yield was not significantly different from the yield in T1 and the control treatments.

The final number of pods per plant is closely correlated with the rate of supply of assimilates during pod filling and irrigation increases assimilate flux by increasing leaf area, growth rate and total dry matter during pod growth (Musallam *et al.*. 2004). Irrigation in T1, T2 and T3 treatments increased the number of pods per plant possibly because of high vegetative growth. Irrigation increases the number of branches per plant and pod retention in beans (Nielsen and Nelson, 1998).

However, the water deficits imposed after pod-filling stage in T4 and T5 treatments may have reduced dry matter distribution to the pods consequently reducing the number of pods per plant as compared to T1, T2 and T3 treatments. The decrease in the number of pods per plant under water deficit is largely due to limited vegetative growth. Leaf initiation, expansion and biomass production might have been significantly reduced by soil water deficits (Barrios *et al.*, 2005).

4.7 Contribution of RDI in profit maximisation

The net profits from respective irrigation options presented in Figure 26 were calculated from the current water price paid by the irrigators in the Herman canal irrigation scheme and the recommended water price for small-scale irrigation in Tanzania according to literature sources. In Herman canal irrigation scheme, the Water Users Association (WUA) charges a non-volumetric price of Tsh 3000 per hectare while in literature irrigation water use in small-scale irrigation furrows is quoted on a volumetric price of Tsh 211 per m^3 (Hellegers, 2005). Comparison of the two pricing strategies was necessary in order to evaluate the economic feasibility of

RDI in the Herman canal irrigation scheme if irrigation water was to be charged on a volumetric basis than the current non-volumetric basis.

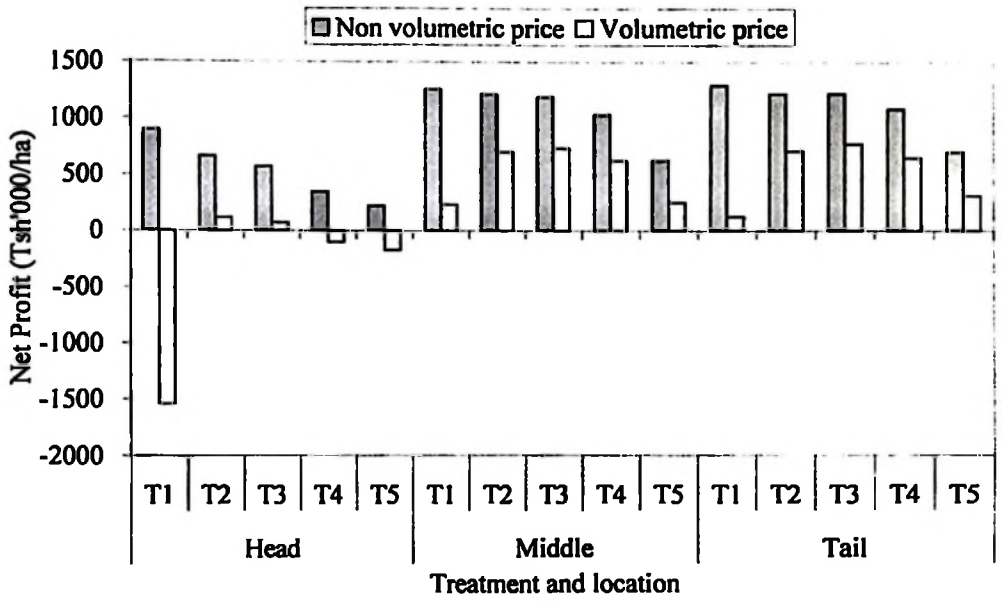

Figure 26: Net profits under different water pricing systems

When the current non-volumetric water pricing was considered, net profits were highest in T1 treatment and lowest in T5 treatment. Therefore, under the current non-volumetric water pricing method, the highest net profits would be realised from higher yields and therefore farmers would continue to apply more water to maximise yield and net profits. However, when the volumetric water pricing method was considered in the analysis, high frequency irrigation and excessive water applications in T1 treatment were associated with very high irrigation costs compared to the control and RDI treatments. In this respect, net profits were highest under RDI in T2 treatment in the Head block and in T3 treatment in the Middle and Tail blocks. Faria

et al. (1997) also found that despite uncertainty, net irrigation returns were positive when irrigation threshold was maintained above 30% of available soil moisture and increased significantly when irrigation threshold was increased up to 50-60% of available soil moisture.

English and Raja (1996) and Perreira (1999) found that where irrigation water is charged on volumetric basis, the potential economic benefits of deficit irrigation are derived from three factors: increased irrigation efficiency, reduced irrigation costs and the opportunity costs of water. In this study, by considering volumetric water pricing, net profits under the farmer managed irrigation were reduced because of increased irrigation costs while in T4 and T5 treatments net profits were reduced because of significant yield reduction arising from high water stress levels. Similar decrease in economic benefits due to severe water deficit were also found on tomato by El Amami *et al* (2001), on wheat by Orloff *et al.* (2003) and on sorghum by Zhang and Pei (2002). Moreover, Cuenca (1989) suggested that greater soil water depletion could be allowed which could result in reduced yield as an economic trade off against the higher costs of irrigation that is more intensive.

The current non-volumetric pricing of irrigation water in the scheme does not have an impact on the farmers' water use in terms of the economic cost of water from their irrigation activities. Therefore, the farmers are misusing water since they do not pay for the actual water price and this is a drawback to water conservation in the scheme. If the volumetric pricing was being used then excessive use of irrigation water would increase irrigation costs and reduce farmers' profits and thus would no longer favour

the farmer managed irrigation practices than the RDI as shown in Figure 26. The farmers are currently benefiting by maximising profits from their irrigation depths because water use is currently virtually free.

4.7.1 Drawbacks to volumetric water pricing in the scheme

In most irrigation schemes that use the non-volumetric water pricing method, most farmers having access to sufficient water are generally not concerned about excessive use of water and in most cases the farmers have little incentives to reduce water input to their field (Rosegrant, 1997). Moreover, the common practice in traditional irrigation systems in which water control is under the ability of the irrigator, as is the case in Herman canal irrigation scheme, the discharges are often largely variable. In most cases, this practice results in over-irrigation due to the irrigators inability to determine correctly the required crop water demand at specific times in the crop growth period (Perreira, 1999; Burton *et al.*, 1999).

As a result, the increases in net profits from the farmers accrue from increase in yields. This study has found that where water is charged on volumetric basis, farmers could reduce the amount of irrigation water and maximise net profits under RDI provided the water deficit is not severe. Therefore, it would be economical to change the practice of irrigating for maximum yield by the farmers in the Herman canal irrigation scheme to irrigating for maximum profits and save large quantities of irrigation water. Low irrigation water pricing has been widely blamed for poor efficiency in irrigation systems as farmers have little incentives to conserve water. With this view being prevalent, raising irrigation water price is a key measure for

dealing with the water shortages (Yang *et al.*, 2003). Lack of volumetric measurement and the high monitoring cost make it difficult to charge water on the actual volume used by each farm household and small fragmented farms scattered around villages further complicate the situation. Therefore charging a flat rate based on land area irrigated is common in surface water irrigated areas.

4.7.2 Challenges in controlling farmers' water use

Theoretically, increasing the water price increases its allocative efficiency and better management. The responsiveness of farmers' water use to increase in price is influenced by many factors including water management systems, market conditions, availability of substitute crops, the degree of freedom in production decision making and the overall economic development (Yang *et al.*, 2003). Shifting to a volumetric water pricing system could be advocated to induce the farmers to adopt RDI strategy to save water and maximise net profits at the cost of reduced yield. However, the volumetric pricing method often results from inadequate information concerning actual consumption quantities or some other way to infer a measurement of water consumption by each irrigator. Apart from relatively high implementation costs associated with volumetric pricing, studies have found that water users' associations (WUA) have a tendency to substantially reduce the costs of implementing water pricing since they are managed by and operated with the interests of water users in mind (Easter and Welsch, 1986; Wade, 1987; Zilberman, 1997).

In an attempt to serve water management and cost recovery objectives, the water rights and taxation system is a big challenge in Tanzania because the practical day-

to-day water management at the grassroots level is still widely influenced by customary arrangements (Sokile and Koppen, 2004). The water rights system fails as a taxation tool in that taxation cannot recover costs of water management nor deter water use in areas without the required water measurement and control structures, which is typical of Tanzania. Procedurally, the water rights system is a wanting, but the application process is unnecessarily long, beaurocratic and time consuming, and moreover it lacks reliable quantification of registered and actual water users. Simultaneously, introducing higher charges for small-scale irrigation water users would be challenged by exacerbating rural poverty and may trigger many political concerns (Yang *et al.*, 2003). Therefore, the WUA would continue to set the non-volumetric water price leading to persistent over-irrigation by the farmers and profits will remain high as long as crop production is maintained or increased.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions can be drawn from the study:

(i) RDI at 50-60% soil moisture depletion can increase water productivity and save significant amounts of irrigation water that can vary depending on the field location with insignificant reduction in yields. The optimal physical and economic returns with irrigation water were obtained at this range of soil moisture depletion during the vegetative stages than in the farmer-managed irrigation.

(ii) Irrigation water applications by farmers in the Herman canal irrigation scheme are higher than crop water requirements. The current non-volumetric water pricing system in the Herman canal irrigation scheme does not have an impact on the farmers' water use in terms of the economic cost of water from their irrigation activities because water use is virtually free. Therefore, this acts as a drawback to water conservation in the scheme as the farmers are misusing irrigation water. If the volumetric pricing was being used then excessive use of irrigation water would increase irrigation costs and reduce farmers' profits and thus would no longer favour the farmer managed irrigation practices

(iii) The yield response factor for the whole scheme suggests that the crop was tolerant to RDI although the bean crop was more sensitive to RDI in the Head block than the rest of the blocks. High deficit levels of RDI reduced the grain yield, number of pods per plant and 100 seeds weight while number of seeds

per pod is a stable yield component in beans. There is a high positive relationship between grain yield and the number of pods per plant than between grain yield and the number of seeds per pod.

5.2 Recommendations

The following recommendations can be drawn from the study:

(i) Irrigation water applications by the farmers in the Herman canal irrigation scheme need particular attention considering the lowest water productivity compared to control and RDI treatments. It is therefore recommended that strategies be formulated aimed at reducing farmers' irrigation frequency and hence seasonal application depths. The farmers should be given enough training on how to reduce their irrigation volumes without affecting water productivity.

(ii) Legislative, institutional and economic measures may be needed to encourage farmers to adopt water productivity enhancing strategies such as RDI in the scheme. Changes in by-laws in future so that the farmers should be paying for water per unit volume used can force farmers to balance irrigation water costs as an input against the returns since over-irrigation will be costly to the farmers.

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APPENDICES

Appendix A: Root zone soil moisture content (mm)

	HEAD					MIDDLE					TAIL				
	Treatment					Treatment					Treatment				
Day	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5
1	74	73	68	81	61	108	65	85	70	55	83	61	62	55	36
2	88	82	72	91	75	101	88	99	85	72	92	68	70	69	61
3	81	79	71	88	72	118	85	96	80	70	87	64	67	65	58
4	77	76	68	86	70	111	82	93	78	67	81	60	65	63	54
5	73	73	66	84	68	104	79	89	75	65	92	57	61	61	52
6	80	71	72	82	68	118	74	87	71	61	87	54	58	59	50
7	77	81	71	79	66	111	91	83	69	57	80	70	55	66	47
8	73	79	69	77	64	104	88	96	66	55	93	67	68	63	45
9	68	77	66	75	63	98	83	75	64	51	87	63	65	61	40
10	90	74	64	73	61	92	79	72	62	50	81	60	62	59	59
11	86	72	71	70	59	88	75	89	60	46	76	56	60	57	57
12	82	71	68	69	56	81	72	86	58	44	71	53	57	54	55
13	80	83	66	89	55	75	85	83	56	41	65	69	53	73	51
14	88	82	65	85	54	120	81	79	54	38	60	64	51	68	46
15	83	77	68	81	72	96	78	99	82	67	97	60	72	66	42
16	78	75	66	79	69	90	75	92	76	63	87	56	67	63	58
17	75	73	65	77	65	100	71	85	72	58	82	52	61	60	54
18	72	71	62	75	59	118	65	79	70	53	76	72	58	57	50
19	69	77	68	73	55	112	84	75	67	49	95	65	55	54	46
20	87	70	64	69	50	107	80	71	63	44	87	61	50	69	43
21	80	62	61	68	47	101	77	68	60	41	80	57	47	64	63
22	74	79	59	94	45	96	73	98	83	55	73	52	67	58	59
23	70	75	71	88	43	114	68	92	78	52	99	50	64	55	55
24	66	71	64	82	68	108	65	85	75	68	91	64	59	53	51
25	84	65	61	78	62	101	62	82	68	63	84	61	53	50	48
26	78	59	56	74	55	116	88	75	63	58	77	56	47	83	62
27	74	81	75	68	51	111	83	70	60	52	71	54	72	75	55
28	81	77	72	67	49	106	78	64	56	45	64	51	65	66	50
29	80	74	68	86	45	100	75	99	74	69	94	46	60	59	46
30	76	66	66	79	66	97	71	94	70	64	88	65	58	55	65
31	72	59	63	81	60	113	67	89	65	59	81	58	54	50	59
32	68	82	67	76	56	105	65	83	61	54	96	54	51	73	52
33	64	74	65	70	52	97	84	77	57	49	89	50	68	64	47
34	79	68	62	66	51	91	81	71	50	45	84	45	63	55	41
35	73	62	61	89	48	85	75	98	81	75	97	61	58	50	66
36	69	57	59	87	46	80	70	92	78	71	87	58	53	42	61
37	63	83	57	83	61	118	65	88	74	63	80	53	50	39	57
38	78	76	53	76	59	110	84	83	70	59	73	51	47	35	52
39	73	69	73	73	56	102	79	80	64	52	65	68	45	29	46
40	67	63	67	68	53	117	76	74	61	48	58	64	68	65	44
41	63	57	63	64	50	108	69	70	56	45	97	59	63	61	42
42	77	78	57	60	45	100	62	66	52	39	87	54	58	56	36
43	72	73	51	55	41	92	58	62	47	36	81	49	53	53	32

44	68	71	68	88	38	115	90	59	43	31	73	63	50	46	64
45	64	68	63	86	65	107	81	86	80	71	87	58	67	41	58
46	78	64	61	84	61	98	76	84	77	69	79	54	61	39	54
47	72	62	57	82	56	92	72	80	73	65	71	48	55	36	52
48	67	58	57	80	52	85	68	72	69	62	64	60	49	32	48
49	64	78	54	74	49	80	61	68	65	60	56	58	42	68	42
50	60	76	76	72	45	72	83	63	61	56	50	53	37	65	38
51	76	71	73	71	42	69	74	59	48	51	47	51	70	60	36
52	72	68	72	67	40	61	71	76	43	46	39	47	64	51	33
53	67	65	70	61	38	53	65	89	37	40	91	67	60	46	30
54	63	61	65	54	37	50	78	81	32	33	83	62	55	39	26
55	60	57	62	50	36	44	73	77	31	31	76	57	50	33	62
56	84	74	58	47	35	121	69	71	29	28	70	53	46	29	60
57	77	70	54	87	34	110	62	67	28	26	63	47	41	26	57
58	71	64	74	86	77	103	40	94	83	76	63	70	70	57	54
59	66	58	71	82	74	95	40	92	76	73	93	67	68	55	49
60	63	51	69	79	70	87	35	89	71	70	83	63	66	54	46
61	59	48	67	76	67	122	66	87	67	68	74	59	64	50	44
62	85	42	66	73	65	113	58	86	62	66	65	52	61	51	41
63	79	77	63	72	64	118	56	81	61	64	59	47	59	48	37
64	73	73	61	70	60	111	49	79	56	61	53	45	56	45	36
65	71	69	57	67	57	104	49	76	50	58	47	69	54	43	33
66	69	63	55	64	52	99	44	73	45	56	93	65	52	40	32
67	85	60	52	60	49	92	38	70	42	53	84	63	50	38	30
68	81	58	49	56	44	86	36	66	38	49	78	60	46	36	28
69	78	55	45	52	39	81	33	64	37	46	73	57	43	35	26
70	74	52	44	51	37	74	31	63	33	43	68	56	40	33	24
71	73	50	42	51	34	72	30	60	32	41	63	53	37	31	23
72	71	48	39	49	32	67	29	58	29	40	61	48	35	29	22
73	69	47	36	46	29	64	27	56	28	37	59	42	32	26	21
74	68	45	34	45	27	63	26	55	26	35	58	40	30	23	19
75	72	44	31	44	25	61	25	54	25	34	57	38	28	22	18

Appendix B: Head block profile soil moisture content (vol %)

	Profile depth														
	0 - 20 cm					20 - 40 cm					40 - 60 cm				
	Treatment					Treatment					Treatment				
Day	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5
1	12	24	11	24	25	40	25	31	32	20	23	25	26	25	16
2	16	33	15	33	33	45	25	31	34	26	27	25	26	25	16
3	12	30	13	30	31	43	25	31	33	26	27	25	26	25	16
4	9	27	11	28	29	42	25	30	33	26	26	25	26	25	16
5	8	24	9	26	27	40	25	30	33	26	26	25	26	25	16
6	16	21	16	24	26	39	25	30	33	26	25	25	26	25	16
7	14	32	14	21	25	38	24	30	33	25	24	25	26	25	16
8	12	30	13	20	23	38	24	30	33	25	23	25	26	24	16
9	9	28	10	17	22	38	24	30	33	25	22	25	26	24	16
10	16	25	8	16	20	45	24	30	33	25	29	25	26	24	16
11	13	23	15	13	18	44	24	29	33	25	28	24	26	24	16
12	10	22	12	12	16	44	24	29	33	25	28	24	26	24	16
13	8	34	10	32	15	44	24	29	33	25	28	24	26	24	16
14	16	33	9	28	14	44	24	29	32	25	28	24	26	24	16
15	14	29	12	25	31	41	24	29	32	25	28	24	26	24	16
16	11	26	10	23	29	39	24	29	31	24	28	24	26	24	16
17	9	24	9	21	27	38	24	29	31	22	27	24	26	24	16
18	7	23	7	20	24	37	24	29	31	20	27	24	26	24	16
19	6	28	14	18	21	36	24	28	31	19	27	24	26	24	16
20	16	24	11	15	19	44	22	27	30	15	27	24	26	24	16
21	14	19	9	15	17	40	19	26	29	14	26	24	26	24	16
22	11	33	6	33	16	37	22	26	37	14	26	24	26	24	16
23	9	31	16	29	15	36	20	29	34	13	25	24	26	24	16
24	6	29	13	25	30	35	19	25	33	22	25	24	26	24	16
25	16	26	10	22	28	43	15	24	31	19	25	24	26	24	16
26	13	23	7	18	24	41	11	23	32	15	25	24	26	24	16
27	11	35	15	14	22	39	22	34	31	13	25	24	26	24	16
28	16	32	14	13	21	41	21	32	30	12	24	24	26	24	16
29	17	31	12	32	19	39	19	30	30	10	24	24	26	24	16
30	14	27	11	28	31	37	15	29	28	19	24	24	26	24	16
31	12	23	9	24	28	36	12	28	32	17	24	24	26	24	16
32	10	32	13	21	24	35	26	28	31	16	24	24	26	24	16
33	7	29	12	15	22	34	21	27	30	14	23	24	26	24	16
34	16	26	9	13	21	40	19	26	29	14	23	24	26	24	16
35	12	22	8	30	19	38	16	26	34	13	23	24	26	24	16
36	10	17	7	29	19	37	16	25	34	11	23	24	26	24	16
37	6	35	6	26	27	34	24	24	33	19	23	24	26	24	16
38	16	31	5	23	27	40	22	21	29	17	22	24	26	24	16
39	12	27	15	22	26	38	18	32	27	14	22	24	26	24	16
40	8	23	12	18	24	37	16	29	27	14	22	24	26	24	16
41	6	19	9	16	23	34	14	28	24	11	22	24	26	24	16
42	16	32	7	14	20	40	21	24	22	10	22	24	26	24	16
43	13	29	4	11	17	38	20	21	19	9	22	24	26	24	16
44	10	26	12	31	15	36	21	30	33	7	21	24	26	24	16
45	8	26	10	30	30	35	18	26	32	20	21	24	26	24	15

46	16	25	9	29	27	41	15	26	31	19	21	24	26	24	15
47	14	24	7	28	23	37	15	24	30	17	21	24	26	24	15
48	11	21	7	27	21	36	13	23	29	16	21	24	26	24	15
49	9	31	6	22	20	35	23	22	28	14	20	24	26	24	15
50	7	30	9	20	17	34	22	40	28	13	20	24	26	24	15
51	16	26	8	18	14	40	21	39	29	12	20	24	26	24	15
52	13	23	7	18	14	37	21	39	25	11	22	24	26	24	15
53	10	20	6	16	14	36	21	37	23	10	21	24	26	22	15
54	8	16	5	13	13	36	21	33	20	9	20	24	26	21	15
55	6	14	4	10	13	35	20	32	19	8	19	24	26	20	15
56	16	29	3	9	13	42	21	29	18	7	26	24	26	20	15
57	13	28	3	31	12	40	19	25	33	7	24	23	26	24	15
58	11	24	11	30	31	38	19	37	32	22	22	22	26	24	24
59	9	23	11	29	29	36	15	34	31	21	21	20	26	22	24
60	7	18	11	28	27	35	13	34	30	21	20	20	25	21	22
61	6	16	11	27	25	34	12	32	29	21	19	19	24	20	21
62	16	14	10	25	24	43	10	32	28	21	26	18	24	20	20
63	14	30	10	25	23	41	23	31	28	21	25	24	23	19	19
64	12	29	10	25	22	39	21	30	27	20	22	24	21	19	18
65	12	27	9	24	23	38	18	27	25	18	21	23	21	18	16
66	11	25	9	23	20	37	15	26	24	16	21	23	20	17	16
67	17	24	8	23	18	42	14	25	21	16	26	22	19	17	15
68	15	23	7	23	15	42	13	23	17	15	24	22	19	16	15
69	14	22	7	22	14	40	12	21	15	14	24	21	17	15	12
70	12	22	7	22	13	39	10	20	14	13	23	20	17	15	11
71	12	21	6	21	13	39	9	20	14	11	23	20	16	15	10
72	11	20	5	21	11	38	9	18	13	10	22	19	16	15	10
73	10	19	5	20	10	38	9	16	12	9	22	18	15	14	10
74	10	19	4	19	9	38	8	15	11	9	21	18	15	14	9
75	10	17	4	19	9	38	7	13	11	8	25	19	14	14	8

Appendix C: Middle block profile soil moisture content (vol %)

	Profile depth														
	0 - 20 cm					20 - 40 cm					40 - 60 cm				
	Treatment					Treatment					Treatment				
Day	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5
1	36	23	23	25	25	37	16	33	26	22	35	26	29	19	9
2	32	31	31	35	33	35	24	38	28	26	34	33	31	22	14
3	43	28	28	31	31	40	23	38	28	25	35	33	30	21	14
4	39	26	25	28	29	38	23	38	28	25	34	33	29	21	13
5	35	24	23	26	27	36	22	37	28	25	33	32	29	21	13
6	43	21	22	24	26	39	21	37	27	24	36	32	29	21	11
7	38	33	19	22	23	38	26	36	26	23	34	32	28	21	10
8	34	30	30	20	23	37	25	37	26	22	33	32	29	20	10
9	30	27	28	19	21	36	24	38	25	21	32	32	29	20	9
10	26	25	26	18	20	34	23	37	25	21	32	31	29	19	9
11	24	23	25	17	17	33	22	36	25	21	31	30	28	19	8
12	20	20	23	16	16	31	22	35	24	21	29	30	28	19	7
13	18	31	21	15	14	29	24	34	23	21	28	30	27	18	7
14	43	28	19	13	12	40	23	34	23	20	37	30	27	17	6
15	20	26	33	31	33	39	22	36	28	23	37	30	30	22	11
16	18	24	30	27	30	36	20	33	27	23	36	30	30	22	10
17	31	23	28	24	28	35	19	28	26	22	34	29	29	22	9
18	42	21	24	22	25	40	17	26	26	20	36	28	28	21	8
19	38	32	22	20	23	39	22	25	26	19	35	30	28	21	8
20	35	29	21	17	20	38	21	23	25	18	34	30	27	21	7
21	31	28	19	16	18	37	20	21	24	16	33	29	27	20	7
22	28	27	33	31	17	36	18	37	30	32	33	28	28	22	6
23	43	24	29	28	16	35	16	35	28	31	36	28	28	22	5
24	39	23	25	26	25	34	14	33	27	30	35	28	28	22	14
25	34	22	23	22	22	33	14	32	25	29	34	27	27	21	11
26	42	31	20	18	20	40	24	28	25	27	35	33	27	21	11
27	39	30	17	15	18	38	21	27	24	25	34	32	26	20	9
28	35	27	16	13	15	38	20	23	23	21	34	31	25	20	9
29	31	26	33	29	27	36	19	37	21	26	33	30	29	23	16
30	26	23	29	27	25	40	18	37	20	24	31	30	28	23	15
31	41	22	26	24	22	37	16	34	19	22	35	29	28	22	14
32	36	21	23	21	19	35	15	33	18	21	34	29	28	21	13
33	32	29	18	19	17	32	24	32	18	19	33	31	27	20	12
34	28	27	14	16	16	30	23	31	15	19	33	30	27	19	10
35	25	24	35	29	33	29	21	35	31	27	31	30	28	22	16
36	22	21	30	26	31	28	19	34	30	25	31	30	28	21	15
37	43	18	28	25	27	39	18	33	28	22	36	29	28	21	14
38	38	29	25	23	27	37	23	31	26	21	35	31	27	21	11
39	34	27	24	20	22	34	22	28	24	19	34	30	27	20	11
40	43	26	23	16	20	39	21	25	24	18	36	29	26	20	10
41	38	21	22	12	18	35	20	23	24	17	35	28	26	20	10
42	35	17	21	10	14	31	18	19	22	16	34	27	25	20	9
43	30	15	19	8	12	28	17	18	19	15	34	26	25	19	9
44	42	29	17	7	7	39	25	17	18	15	35	35	25	19	8
45	38	24	30	35	32	35	24	30	25	25	34	32	26	20	14

46	34	23	29	33	31	31	23	29	24	24	33	31	26	19	14
47	31	21	27	30	29	28	21	28	24	23	32	30	25	19	13
48	27	18	23	28	28	26	21	24	23	22	32	29	25	19	13
49	23	13	20	26	26	23	19	23	22	21	33	28	25	17	12
50	20	31	18	24	25	21	21	21	20	20	31	31	24	17	11
51	17	29	16	22	23	17	15	20	18	19	35	30	23	7	9
52	14	28	33	20	21	14	14	32	17	17	33	29	11	7	8
53	11	25	29	14	18	11	12	30	16	16	31	29	30	7	6
54	10	27	25	12	15	9	23	27	14	14	31	28	30	6	5
55	9	23	22	10	13	5	23	26	14	13	29	27	29	7	4
56	42	22	19	9	12	39	21	23	13	12	40	27	29	7	4
57	38	16	17	9	11	36	19	21	12	11	36	26	28	7	4
58	35	14	32	31	35	33	18	30	31	27	35	26	32	21	14
59	31	13	30	29	34	30	17	30	29	25	34	24	32	18	13
60	28	12	28	28	34	26	17	28	27	24	33	24	32	16	13
61	42	28	28	27	33	39	23	28	26	23	41	23	31	14	12
62	39	24	27	26	31	36	21	28	24	23	38	23	31	12	12
63	43	22	26	26	30	39	22	27	23	23	37	23	29	12	11
64	39	19	25	23	30	37	20	26	21	23	35	20	28	12	9
65	36	18	24	19	28	35	20	24	19	22	33	21	27	11	8
66	34	15	23	18	28	33	19	24	17	21	32	20	25	9	7
67	31	13	22	17	27	30	17	22	17	20	32	18	26	9	7
68	28	12	21	14	26	27	17	21	16	19	32	18	24	8	7
69	26	10	19	14	24	24	16	21	16	19	31	17	23	7	7
70	21	9	18	12	22	22	15	21	14	18	31	17	23	7	6
71	20	9	18	11	21	20	14	20	14	17	31	17	22	7	6
72	19	9	17	9	20	18	14	19	13	17	31	17	22	7	5
73	17	8	16	8	19	16	13	18	13	16	31	16	22	7	5
74	17	7	16	7	18	15	13	18	12	15	31	16	21	7	5
75	15	7	15	6	17	15	12	17	12	15	31	16	21	7	5

Appendix D: Tail block profile soil moisture content (vol %)

	Profile depth														
	0 - 20 cm					20 - 40 cm					40 - 60 cm				
	Treatment					Treatment					Treatment				
Day	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5
1	24	20	19	15	15	23	19	17	11	8	36	22	26	28	13
2	29	21	23	22	20	25	23	19	17	22	37	23	28	30	19
3	26	20	22	18	19	24	22	19	17	21	36	22	27	30	19
4	22	18	20	17	17	24	21	18	17	20	35	21	27	29	18
5	30	16	18	16	15	25	21	18	16	19	36	20	26	29	18
6	26	14	15	14	14	24	20	17	16	18	36	20	26	28	18
7	22	23	13	19	13	23	23	17	16	17	35	24	25	30	17
8	30	21	22	18	11	24	23	22	16	17	39	23	24	30	17
9	26	19	21	16	8	24	22	21	15	15	37	22	23	29	17
10	22	18	19	15	18	22	21	20	15	20	36	21	23	29	21
11	19	15	18	14	17	21	21	19	15	20	35	21	23	28	20
12	16	14	15	11	16	20	19	19	15	19	34	20	22	28	20
13	13	21	14	23	14	19	24	19	20	17	33	23	21	31	19
14	9	18	13	19	10	18	23	18	19	17	33	23	20	30	19
15	30	16	22	18	8	27	22	24	19	16	40	22	26	29	19
16	26	14	21	16	21	24	21	21	19	18	37	21	25	29	18
17	23	12	18	14	19	23	20	19	17	17	36	21	25	28	18
18	19	22	15	13	18	21	25	18	17	14	35	24	24	28	18
19	30	19	14	11	16	29	23	18	15	13	36	23	23	27	17
20	26	17	12	22	15	26	21	16	15	11	35	23	23	33	17
21	22	16	10	19	19	23	19	14	14	21	35	22	23	31	23
22	18	14	21	16	17	21	17	22	12	20	34	21	24	30	22
23	30	13	19	13	15	29	16	22	12	20	40	20	23	29	21
24	26	17	15	12	13	27	23	20	12	18	39	23	23	29	19
25	22	16	11	11	11	25	22	20	11	18	37	23	22	28	19
26	18	14	8	24	19	23	20	18	24	21	36	22	21	35	21
27	14	12	23	22	15	21	20	24	20	19	36	21	25	33	20
28	10	11	19	20	14	19	18	22	15	17	35	21	25	31	19
29	30	11	16	16	11	30	14	20	13	16	34	20	24	30	19
30	26	21	14	14	21	29	22	21	11	23	33	22	24	30	21
31	23	18	11	11	19	27	20	20	10	21	31	21	23	29	19
32	30	16	9	22	14	30	18	20	20	18	36	19	23	31	19
33	26	15	23	18	12	29	16	22	16	17	34	19	23	30	18
34	22	14	21	14	10	27	14	20	13	14	35	17	22	29	17
35	30	18	20	11	22	29	20	17	10	23	37	22	21	29	22
36	26	17	17	10	20	26	20	15	9	20	35	21	21	28	21
37	22	14	16	9	19	23	19	14	7	19	35	20	20	28	19
38	17	13	15	8	18	21	18	13	6	16	34	20	19	27	19
39	14	21	14	7	16	18	23	11	5	13	33	24	19	26	17
40	10	20	22	21	15	15	21	23	14	12	33	23	23	30	17
41	30	18	20	19	14	28	18	21	12	11	39	22	23	30	17
42	25	17	18	17	11	25	16	18	10	9	37	21	22	29	16
43	22	14	15	15	10	23	14	16	10	7	35	20	22	28	16
44	18	19	15	12	23	21	22	14	7	17	35	22	21	28	24
45	25	17	22	11	19	24	20	23	9	15	37	21	23	27	23

46	21	16	19	10	16	21	18	20	9	15	36	20	23	27	23
47	17	13	15	9	17	19	15	17	7	13	35	20	22	27	22
48	13	18	13	8	14	17	20	15	6	12	34	22	21	26	22
49	10	17	9	23	11	13	20	12	14	10	33	21	21	31	21
50	9	14	10	21	7	11	19	6	14	10	33	20	21	30	21
51	8	13	21	18	8	8	18	23	13	8	34	19	26	29	21
52	7	13	16	14	6	5	15	22	10	7	33	19	25	27	20
53	29	22	14	12	6	26	22	21	9	5	36	23	25	25	20
54	26	22	11	10	5	22	19	20	8	4	35	22	24	24	19
55	23	20	8	8	22	19	16	20	7	23	34	21	22	23	17
56	21	17	6	7	21	16	15	19	6	23	33	21	20	22	16
57	19	14	4	6	20	12	13	18	5	20	33	19	19	20	16
58	22	23	22	23	20	9	23	22	19	19	32	25	26	14	16
59	30	21	21	22	17	26	21	21	19	17	36	25	25	13	15
60	26	19	20	21	15	23	20	21	20	17	34	24	25	12	14
61	22	18	19	19	14	19	18	20	19	17	33	23	25	12	13
62	19	15	18	20	12	15	16	19	19	16	31	22	24	12	12
63	17	13	17	19	11	12	14	19	19	16	30	20	23	10	11
64	14	12	16	18	10	9	14	18	17	15	29	19	22	10	11
65	12	24	15	17	9	7	21	18	17	14	28	24	22	9	9
66	30	22	14	16	9	26	20	17	16	13	36	23	21	8	9
67	25	21	14	15	10	24	19	15	15	12	35	23	21	8	8
68	24	19	12	15	9	21	18	15	14	10	34	23	20	7	8
69	22	18	10	14	9	19	18	14	14	10	32	21	19	7	7
70	20	17	8	13	9	17	17	14	14	9	31	21	18	6	6
71	18	16	6	12	9	16	16	14	13	9	30	20	17	6	6
72	16	14	6	11	9	14	16	13	12	9	30	19	16	6	5
73	15	10	5	9	9	14	14	12	11	8	30	18	15	6	5
74	14	10	4	8	9	14	13	11	10	6	30	17	15	5	4
75	14	9	4	8	8	14	12	11	9	6	30	17	13	5	4

Appendix E: Cumulative crop water use (mm)

	Head					Middle					Tail				
Day	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5
1	3	2	2	2	2	3	2	2	2	2	3	2	2	1	2
2	8	4	4	4	4	7	4	3	5	4	7	5	4	3	4
3	12	5	6	5	6	11	6	5	7	6	11	8	6	4	6
4	16	7	8	6	7	15	9	7	9	8	15	11	9	5	7
5	20	9	10	7	9	19	12	9	11	9	19	14	10	7	9
6	24	11	11	8	11	23	15	12	14	10	23	16	13	8	10
7	28	12	13	10	12	28	17	14	15	12	27	18	16	10	11
8	31	14	16	11	14	32	20	15	18	13	30	20	18	11	14
9	34	16	17	13	15	36	22	17	19	15	34	23	20	12	16
10	37	18	19	14	17	40	25	18	22	17	38	24	22	13	17
11	41	20	22	15	19	44	27	21	23	20	42	26	23	16	19
12	44	23	25	17	21	47	29	22	26	20	46	28	25	17	21
13	48	26	28	19	23	50	33	23	29	21	49	29	27	21	24
14	51	29	30	21	25	53	35	25	33	22	52	33	29	22	26
15	54	31	31	23	28	56	36	28	35	24	56	36	33	24	28
16	58	34	33	26	30	58	37	32	37	26	60	38	37	26	31
17	61	37	36	27	32	62	40	35	38	30	64	40	42	27	33
18	64	42	38	30	35	67	42	37	41	33	68	41	45	28	36
19	65	45	42	33	37	71	44	40	43	35	73	46	47	29	38
20	70	46	44	35	39	75	46	43	44	37	78	53	49	32	41
21	74	50	48	36	40	79	49	45	45	38	84	56	51	36	43
22	77	51	52	39	41	85	52	47	50	39	90	58	54	39	46
23	81	54	57	42	42	91	54	51	55	40	96	62	59	40	48
24	83	56	60	46	45	96	56	56	59	45	102	66	62	42	50
25	89	59	64	50	48	101	58	60	63	48	107	70	66	43	53
26	94	61	68	53	51	106	61	64	68	50	112	73	70	48	58
27	97	63	71	55	54	110	64	69	69	52	117	77	74	52	61
28	101	65	73	56	57	114	66	72	72	54	123	79	78	57	64
29	102	67	75	59	61	118	69	75	77	56	128	85	82	60	68
30	105	71	78	62	64	122	71	78	78	61	132	91	86	64	72
31	109	76	81	65	67	126	73	80	82	64	138	95	90	67	76
32	114	80	83	68	70	131	75	82	86	67	145	101	94	72	79
33	117	83	86	72	71	136	78	86	88	69	152	105	99	79	82
34	123	86	89	76	72	141	82	91	91	71	156	109	103	83	85
35	128	88	91	80	75	145	86	95	93	72	162	115	108	84	89
36	131	92	93	83	78	149	89	97	97	73	169	119	112	87	92
37	136	93	97	87	80	155	92	99	100	75	174	125	116	90	96
38	141	96	99	92	83	161	96	101	103	79	180	131	119	94	101
39	146	100	105	96	87	166	98	103	108	82	185	137	124	97	103
40	151	104	109	100	90	171	104	106	112	85	190	143	128	102	105
41	155	107	116	103	93	176	110	111	116	90	196	146	131	105	109
42	159	112	121	107	96	181	113	116	119	94	202	150	135	108	112
43	162	116	126	110	99	187	116	118	123	97	206	152	138	112	115
44	167	119	131	113	102	193	122	120	125	100	211	155	141	116	119
45	172	123	132	116	104	199	125	125	126	104	217	159	142	118	122
46	177	128	136	119	108	204	129	131	128	107	222	161	145	121	124
47	182	132	138	123	110	209	132	136	131	111	227	165	148	124	127

48	185	133	140	126	112	214	138	142	135	113	232	168	152	127	133
49	191	138	143	129	114	219	142	147	136	118	237	170	157	130	136
50	196	139	146	133	117	223	150	152	138	121	242	175	160	134	138
51	201	142	148	137	120	229	152	157	141	123	247	179	163	139	141
52	206	145	151	140	123	233	157	161	146	124	251	181	167	143	144
53	211	149	156	144	126	238	162	165	150	126	256	186	170	149	146
54	216	153	159	146	129	244	167	168	153	127	262	189	174	153	149
55	219	157	162	148	131	247	170	171	155	128	267	192	177	156	151
56	223	161	167	149	132	252	177	174	158	129	271	196	181	159	154
57	227	165	171	150	133	258	180	177	160	130	275	201	184	161	157
58	232	168	174	153	135	263	182	179	163	133	279	207	187	162	160
59	235	172	177	156	138	269	184	180	165	136	285	211	190	165	162
60	237	176	179	158	139	275	186	182	168	138	292	214	191	169	164
61	242	182	181	161	142	281	193	185	170	140	299	219	192	171	166
62	246	186	183	162	143	287	195	187	171	141	305	222	195	173	169
63	251	187	186	165	145	292	201	190	173	144	309	225	197	175	171
64	255	190	190	168	148	298	202	191	176	146	314	229	200	176	173
65	256	194	191	170	149	303	206	194	178	151	317	235	202	178	174
66	258	196	194	173	151	306	210	196	181	154	319	237	205	179	175
67	260	198	197	175	154	311	212	199	183	158	326	240	208	181	177
68	263	201	200	176	156	316	215	202	186	161	330	242	210	183	179
69	265	202	202	178	160	319	217	205	187	163	334	245	211	184	180
70	268	205	203	179	162	323	217	207	188	165	336	246	213	186	181
71	269	208	207	180	162	325	218	209	190	168	337	248	216	188	181
72	270	212	209	181	163	328	220	211	192	170	339	250	217	190	182
73	271	214	211	182	164	330	221	213	193	172	339	252	218	193	184
74	272	216	213	183	166	330	222	215	194	173	341	254	219	194	185
75	272	218	215	184	167	333	223	217	195	175	341	256	220	195	187

Appendix F: Crop water use at specific growth periods

Growth stage	Treatment	Location			Mean
		Head	Middle	Tail	
Pre-flowering	T1	77	85	90	84
	T2	51	52	58	54
	T3	47	52	54	51
	T4	39	39	50	43
	T5	39	41	46	42
Flowering and pod filling	T1	119	138	151	136
	T2	88	98	117	101
	T3	94	104	106	101
	T4	94	87	95	92
	T5	76	82	92	83
Post flowering	T1	76	99	109	95
	T2	73	79	81	78
	T3	60	65	69	65
	T4	52	57	61	56
	T5	49	49	54	51

Appendix G: Yield and yield components

Yield component	Treatment	Location			Mean
		Head	Middle	Tail	
Pods per plant	T1	8.3	10.2	11.1	9.9
	T2	8.3	10.4	10.8	9.8
	T3	8.2	10.3	10.4	9.6
	T4	7.6	8.8	8.7	8.4
	T5	7.3	8.5	8.3	8.0
Seeds per pod	T1	4.5	4.5	4.6	4.5
	T2	4.4	4.5	4.5	4.5
	T3	4.3	4.4	4.5	4.4
	T4	4.3	4.4	4.4	4.4
	T5	4.2	4.3	4.3	4.3
100 seeds (g)	T1	44.8	51.2	50.6	48.9
	T2	44.5	49.7	49.2	47.8
	T3	43.1	46.4	47.2	45.6
	T4	39.2	45.5	45.8	43.5
	T5	36.7	41.3	41.2	39.7
Grain yield (kg/ha)	T1	2387	2839	2886	2704.0
	T2	2064	2754	2761	2526.3
	T3	1934	2712	2751	2465.7
	T4	1640	2496	2562	2232.7
	T5	1468	1970	2067	1835.0

Appendix H: Physical and economic productivity of water

	Treatment	Location			Mean
		Head	Middle	Tail	
Crop water use (mm)	T1	272	332	340	315
	T2	256	223	218	232
	T3	215	220	217	217
	T4	195	184	195	191
	T5	175	167	187	176
Irrigation water (mm)	T1	1159	489	557	735
	T2	263	247	245	252
	T3	239	220	217	225
	T4	216	197	210	208
	T5	192	179	188	186
Grain yield (kg/ha)	T1	2387	2839	2886	2704.0
	T2	2064	2754	2761	2526.3
	T3	1934	2712	2751	2465.7
	T4	1640	2496	2562	2232.7
	T5	1468	1970	2067	1835.0
WP_{Y_IRR} (kg/ m^3)	T1	0.21	0.58	0.52	0.43
	T2	0.78	1.11	1.13	1.01
	T3	0.81	1.23	1.27	1.10
	T4	0.76	1.27	1.22	1.08
	T5	0.76	1.10	1.10	0.99
WP_{Y_ETa} (kg/ m^3)	T1	0.88	0.86	0.85	0.86
	T2	0.81	1.23	1.27	1.10
	T3	0.90	1.23	1.27	1.13
	T4	0.84	1.36	1.31	1.17
	T5	0.84	1.18	1.11	1.04
WP_{GVP_IRR} (Tsh/ m^3)	T1	165	464	415	348
	T2	628	892	902	807
	T3	647	986	1014	883
	T4	607	1014	976	866
	T5	612	880	880	791
WP_{GVP_ETa} (Tsh/ m^3)	T1	702	684	679	688
	T2	645	988	1013	882
	T3	720	986	1014	907
	T4	673	1085	1051	936
	T5	671	944	884	833