Landwirtschaftliche Fakultät

Water productivity in medium and small reservoirs in the Upper East Region (UER) of Ghana

Inaugural-Dissertation

zur

Erlangung des Grades

Doktor der Agrarwissenschaften

(Dr. agr.)

der Hohen Landwirtschaftlichen Fakultät

der

Rheinischen Friedrich-Wilhelms-Universität

zu Bonn

vorgelegt am 25.03.2008

von

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Tag der Promotion: 25.03.2008

Erscheinungsjahr: 2008

Diese Dissertation ist auf dem Hochschulschriftenserver der ULB Bonn
http://hss.ulb.uni-bonn.de/diss_online elektronisch publiziert

KURZFASSUNG

Die Verbesserung der Wasserproduktivität (WP) ist eine wichtige Strategie zur Lösung der zukünftigen Wasserknappheit, verursacht hauptsächlich durch die wachsende Bevölkerung und den potenziellen Klimawandel. Obwohl Kenntnisse über die WP notwendig sind, um verbesserte Wasserbewirtschaftungsstrategien entwickeln zu können, ist wenig über die WP bewässerter Systeme in Subsahara-Afrika (SSA) und insbesondere in der Upper East Region (UER), Ghana, bekannt. In dieser Studie werden die verschiedenen Nutzungen von Stauseewasser beschrieben und die WP in landwirtschaftlichen Anbauflächen, in der Viehwirtschaft und in der Fischerei ermittelt. Außerdem werden die Faktoren, die den Wert des Bewässerungswassers im Tomatenanbau bestimmen, bewertet. Zwei Stauseen in der UER wurden für die Studie ausgewählt: ein mittelgroßer Stausee in Tono und ein kleiner in Dorongo.

Auf der Grundlage von Felddaten aus der Trockenzeit sowie Sekundärdaten werden die verschiedenen Nutzungen des Stauseewassers beschrieben. Klima- und Bodendaten sowie Angaben über Mengen des Bewässerungs- bzw. Abflusswassers wurden eingesetzt. Bezugsdaten hinsichtlich Evapotranspiration sowie Wasserverbrauch der Anbaupflanzen wurden aus den Klimadaten mit der FAO-Penman-Monteith-Methode ermittelt. Die bodenphysikalischen und -hydraulischen Eigenschaften wurden bestimmt. Mit dem Boden-Wasser-Atmosphäre-Pflanze-Modell (SWAP) wurde der Bodenwasserhaushalt auf Versuchsflächen auf Farmen in den Untersuchungsgebieten berechnet. Die bodenhydraulischen Eigenschaften und die Parameter der Pedotransferfunktionen im SWAP-Modell wurden aus den physikalischen Bodeneigenschaften mit dem Rosetta-Modell ermittelt. Die Parameter wurden mit einem nichtlinearen Parameterschätzverfahren (PEST) bestimmt. Auf Farm- und Bewässerungssystemebene wurde der Wasserhaushalt auf der Grundlage der Messungen von Wasserzufluss bzw. -abfluss herkömmlich bestimmt. Mit dem Ergebnis dieser Analyse wurde die physikalische WP der bewässerten Anbaupflanzen auf Feld-(Versuchsfläche), Farm- und Systemebene ermittelt. Die WP wurde als Verhältnis zwischen Erntemengen und den Wasserhaushaltsparametern Transpiration, Evapotranspiration und Bewässerungswassermenge berechnet. Um den Wert des Wassers (wirtschaftliche WP) in der Tomatenbewässerung zu ermitteln, wurde eine Rest imputation Methode mit Daten aus einer Befragung ausgewählter Farmer eingesetzt. Mit dem gross margin Ansatz wurde der Wert des Wassers in Viehwirtschaft und Fischerei auf der Grundlage der eingesetzten Produktionsmittel und dem Volumen des Stauseewassers, das von Viehzucht oder Fischerei benötigt wurde, berechnet. Mit einer multivarianten linearen Regressionsanalyse wurde der Beitrag der Produktionsfaktoren zum Wert des Bewässerungswassers beim Tomatenanbau ermittelt.

Die Ergebnisse der Bodenwasserhaushaltsanalyse zeigen, dass die Versuchsflächen 11 bis 70% überbewässert wurden. Überbewässerung führte zu signifikanten Wasserverlusten und eine erheblich niedrigere Wassereffizienz in Tono als in Dorongo. Die physikalische WP war höher in Dorongo als in Tono; die Werte an beiden Standorten sind aber nicht höher als die wenigen vorhandenen WP-Daten für SSA, jedoch unter den Werten für Flächen außerhalb SSA. Der Beitrag des Bewässerungswassers zum Gesamtwert der Tomatenproduktion ist hoch. Dies deutet daraufhin, dass Wasser eine Schlüsselrolle im Anbau während der Trockenzeit spielt. Der imputed Wert des Wassers unterscheidet sich signifikant innerhalb der Standorte, jedoch nicht zwischen den Standorten. Dieser Wert wird signifikant durch Standort, Erntemenge und Produktpreis beeinflusst. Obwohl der Wert des Wassers für Viehwirtschaft und Fischerei niedriger ist als der Wert im Tomatenanbau, ist diese Information wichtig für die jahreszeitliche Planung der Nutzung des Stauseewassers und demonstriert die Bedeutung von Wasserzuteilungen in den einzelnen Wirtschaftsbereichen vor dem Hintergrund der konkurrierenden Nutzungen.

Die Ergebnisse der Studie zeigen, dass die WP im Untersuchungsgebiet niedrig ist und dass ein großes Verbesserungspotenzial für die Wasserbewirtschaftungsorganisationen und Farmer existiert. Außerdem wird die Rolle der staatlichen Unterstützung bei der Sicherung eines

stabilen Marktes für leichtverderbliche Produkte als ein entscheidender Anreiz für die Farmer, in Strategien für verbesserte WP zu investieren, unterstrichen.

ABSTRACT

Improving water productivity (WP) is one important strategy for addressing future water scarcity, which is driven particularly by increasing human population and potential climate changes. Although an understanding of WP is required to develop improved water management strategies, little is known about WP in irrigated systems in sub-Saharan Africa (SSA) and the Upper East Region (UER), Ghana, in particular. To address this problem, this study was conducted in the UER during the dry season to describe the multiple uses of reservoir water, estimate WP for crop, livestock and fishery water uses, and to assess the factors contributing to the value of irrigation water for tomato farming. Two sites were selected: a medium reservoir at Tono and a small reservoir at Dorongo.

The multiple uses of reservoir water were described using onsite field observations and secondary data. Climatic, soil, irrigation supply, and drainage data were collected. Reference crop evapotranspiration and crop water use were estimated from the climatic data using the FAO-Penman Monteith approach. Soil data were analysed for physical and hydraulic properties. The SWAP model was used to estimate soil water balances at field scale using farmer-managed sample plots. Soil hydraulic properties and parameters of the pedotransfer functions in SWAP were estimated from physical soil properties using the Rosetta model. The parameters were optimized with PEST. At farm and scheme scales, the soil water balance analysis was determined conventionally based on the measurements of irrigation water inflows and outflows. The soil water balance analysis was used to assess physical WP of irrigated crops at field (plot), farm and scheme scales. Crop yield data were collected and the WP was estimated as the ratio of crop yield to the water balance components: transpiration, evapotranspiration, and irrigation water. A residual imputation method was used to determine the value of water (economic WP) for tomato irrigation using data collected from a questionnaire survey adminstered to a sample of farmers. The gross margin approach was used to estimate the value of water for livestock and fishery based on production inputs and the volume of reservoir water depleted by the livestock or required for fisheries maintainance. The multiple linear regression analysis was used to assess the contribution of the production factors to the value of irrigation water for tomato farming.

The soil water balance analysis shows that plots were over-irrigated by 11 to 70%. Over-irrigation contributed to a significant water loss and very low water use efficiency at Tono. Physical WP was higher at Dorongo than at Tono. The WP values at both sites were not higher than the few WP estimates available for SSA. However, WP values were below those reported for outside SSA. The contribution of irrigation water to the total value of tomato production was high, suggesting that water plays a key role in dry season farming. The imputed value of water differs significantly among the indicators used within sites, but was not significantly different between sites. This value was found to be significantly influenced by location, crop yield and the price of the commodity. Although the value of water for livestock and fishery uses were lower than that for irrigated tomato farming, it provide important information for seasonal planning of reservoir water resources management under multiple water uses and demonstrate the importance of water allocation for the sectors given competing uses.

The study concludes that WP in the study area is low, and that a potential for improvement exists within the reach of the management agencies of reservoir water resources and the farmers. The study also underscores the role of government support in ensuring that a secure market exists for perishables as an essential incentive for the farmers to invest in strategies to improve WP.

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LIST OF ABBREVIATIONS

ADCRH	Level of high atmospheric demand
ADCRL	Level of low atmospheric demand
AEZs	Agro-Ecological Zones
API	Asset Price Index
CGIAR	Consultative Group on International Agricultural Research
CH	Crop height
CWU	Crop water use
DDT	Dichloro-Diphenyl-Trichloroethane
DMC	Damsite Management Committee
DMR	Dry matter requirement
D_{root}	Root layer thickness
DSS	Decision Support System
E	Evaporation
E_{nb}	Non-beneficial evaporation
E_{p}	Potential Evaporation
ET_a	Actual Evapotranspiration
ET	Evapotranspiration
ET_{p}/ET_o	Potential evapotranspiration
FAO	Food and Agriculture Organization of the United Nation
FC	Field Capacity
GDP	Gross Domestic Product
GIDA	Ghana Irrigation Development Authority
GIS	Geographical information systems
GMS	Ghana Meteorological Services
GPS	Global Positioning System
GVD	Glowa Volta Database
GVPP	Glowa Volta Project Proposal
h	Soil water pressure head
I	Irrigation
ICOUR	Irrigation Company of the Upper Region
ISZ	Interior Savanna Zone
ITCZ	Intertropical Convergence Zone

IWMI	International Water Management Institute
K_c	Crop factors
KDIF	Light extinction coefficients for diffuse visible light
KDIR	Light extinction coefficients for direct visible light
KOISP	Kirindi Oya Irrigation System Project
K_y	Yield response factors
LACOSREP	Land Conservation and Smallholder Rehabilitation Project
LAI	Leaf Area Index
LCC	Length of Crop Cycle
LFWD	Livestock feed water depletion
LTFs	Long Throated Flumes
MCM	Million Cubic Meters
ME	Mean Error
MOFA	Ministry of Food and Agriculture
MUS	Multiple Use System
ND	Number of days
NPK	Nitrogen Phosphorus Potassium Compound Fertilizer
PEST	Parameter Estimator
PET	Potential Evapotranspiration
PFP	Partial factor productivity
P_i	Rainfall/precipitation interception
PTF	Pedotransfer functions
PVC	Polyvinyl chloride
PWP	Permanent wilting point
R	Correlation coefficient
R^2	Coefficient of determination
RD	Rooting depth
Reg	Regression
RH	Relative Humidity
RMSE	Root Mean Square Error
RSC	Canopy resistance [cm^{-1}]
SA	Sulphate of Ammonia Fertilizer
SCF	Soil cover fractions
SD	Surface drains

SRI	Soil Research Institute
SSA	Sub-Saharan Africa
SWAP	Soil-Water-Atmosphere-Plant Agro-hydrological Model
TF	Tolerance Factors
TLU	Tropical Livestock Units
T_p	Potential Transpiration
TSUMAM	Temperature sum from anthesis to crop maturity
TSUMEA	Temperature sum from crop emergence to anthesis
UDET	Unit dry matter evapotranspiration
UER	Upper East Region
UN	United Nations
UNDP	United Nations Development Programme
USA	United States of America
USD	United States Dollars
VCs	Village committees
VIF	Variance Inflation Factors
VRB	Volta River Basin
VW	Value of Water
WP_{ET}	Evapotranspirational Water Productivity
WP_I	Irrigation Water Productivity
WP_T	Transpirational Water Productivity
WP	Water Productivity
WRC	Water Resources Commission
WUA	Water Users' Association
WUE	Water Use Efficiency
WVR	White Volta River
ZMF	Zone M Farm in Tono
ΔW	Change in soil water storage
¢	Ghanaian Cedis

LIST OF SYMBOLS

		Units
λ	Empirical coefficient	[-]
θ	Soil moisture	[cm^3cm^{-3}]
γ_a	Psychrometric constant	[kPa^0C^{-1}]
θ_{res}	Residual water content	[cm^3cm^{-3}]
θ_{sat}	Saturated water content	[cm^3cm^{-3}]
λ_w	Latent heat of vaporization	[$MJkg^{-1}$]
C	Differential soil water capacity	[cm^{-1}]
c_p	Specific heat of the air	[$MJkg^{-1}\,^0C^{-1}$]
e_s/e_a	Saturated/actual vapour pressure of the air	[kPa]
G	Soil heat flux	[$MJm^{-2}d^{-1}$]
H	Pressure head	[cm]
K	Hydraulic conductivity	[cmd^{-1}]
K_{sat}	Saturated hydraulic conductivity	[cmd^{-1}]
n	Empirical shape factor	[-]
Q	Flow rate	[m^3s^{-1}]
Q_{bot}	Water percolation at the soil column bottom (+upward)	[mm]
r_a	Aerodynamic resistance	[sm^{-1}]
r_c	Crop resistance	[sm^{-1}]
R_n	Net radiation	[$MJm^{-2}d^{-1}$]
$S_a(h)$	Root water extraction rate	[d^{-1}]
S_e	Relative saturation	[-]
U_2	Wind speed at 2m height	[ms^{-1}]
z	Rooting depth	[cm]
z	Vertical coordinate	[cm]
α	Empirical shape factor	[cm^{-1}]
α_{rs}	Reduction factors for water	[-]
Δ	Slope of the saturation vapour pressure curve	[kPa^0C^{-1}]
κ_{gr}	Extinction coefficient for global solar radiation	[-]
ρ_a	Mean air density at constant pressure	[kgm^{-3}]

1 INTRODUCTION

1.1 General introduction and problem definition

Climate change, population increase and economic development within a fixed resource base are among the key drivers of increased water scarcity in developing countries (Qadir et al., 2007; Rijsberman and Manning, 2006). Rijsberman (2004) defines water scarcity as a situation characterized by water insecurity of a large number of people in an area for a prolonged period of time. There is no universally accepted definition of water scarcity, and several indicators of water scarcity are used (Sulivan, 2002; and UNDP, 2006). Increased competition for water between agriculture and other sectors such as the environment and urban water demand is one of the expected consequences of water scarcity (Tropp et al., 2006). While many sectors may experience water stress, irrigated agriculture, which accounts for about 80% of blue water withdrawals in developing countries (UNDP, 2006), will face the real problem of water scarcity. Water stress is a situation occurring when water demand exceeds available supply during a certain period (UNEP, 2004), and blue water is the combination of surface and renewable groundwater resources (Savenije, 1998). The inability of irrigated agriculture to compete economically with other sectors for water further compounds the problem of water scarcity in irrigated agriculture. The estimated value of water for irrigated agriculture is typically below the value of water in urban sectors. Urban demands thus out-compete irrigation demand, and water is reallocated from irrigation to satisfy the rapidly growing urban and industrial demand in developing countries (Rijsberman and Manning, 2006; Qadir et al., 2007; UNDP, 2006). However, many of the developing countries have agriculture-based economies, and water supply for agriculture will continue to play a key role in meeting demands for food for the growing population and in supporting the livelihoods of the poor majority.

Although Ghana, like many sub-Saharan African (SSA) countries is projected to experience economic rather than physical water scarcity by 2025 (IWMI, 2000), geographically disadvantaged settings within Ghana such as the Northern Regions often face severe physical water scarcity far beyond what is suggested by national average per capita water resources figure. A country with adequate water resources but lacking capacity to develop water infrastructure to supply water is referred to as economically water scarce, whereas a country with water resources insufficient to support its population experiences physical water scarcity (IWMI, 2000). As Cook et al. (2006a) point out, most water-scarce regions coincide with regions where most of the poor and food-insecure people live. The Upper East Region (UER), one of Ghana's northern regions is a typical case.

Improving water productivity (WP), a measure of performance generally defined as the physical quantity or economic value derived from the use of a given quantity of water (Molden et al., 2003), is one important strategy towards confronting future water scarcity. Increasing WP to obtain higher output or value for each drop of water used can play a key role in mitigating water scarcity (Molden et al., 2001; UNDP, 2006). Global projections show that increases in WP and expansion of irrigated areas are required to account for half of the long-term increase in global water requirements for a food supply that will ensure food security of the projected 2050 population (Tropp et al., 2006). Further, projected increases of WP by 30% and 60% in rain-fed and irrigated agriculture, respectively, are required to meet the demands for food security for the period 2000-2025 (Cook et al., 2006a; Rijsberman and Molden, 2001). WP is currently considered a more appropriate indicator of water system performance than the most widely used efficiency indicators, both classical and neo-classical (Seckler et al., 2003). Under classical efficiency indicators, surface and groundwater drainage are counted as losses even when beneficially reused downstream, while neoclassical efficiency integrates water recycling into the concept of water-use efficiency (Sekler et al., 2003; Xie et al., 1993). Unlike irrigation efficiency indicators, WP provides more information on the amount of output that can be produced with a given amount of water (Guerra et al., 1998). Also, WP can capture differences in the value of water for alternative uses (Wichelns, 2002). However, physical WP is not different from water-use efficiency (WUE) when expressed in terms of yield per unit amount of water consumed.

Water productivity may vary when evaluated at different spatial scales due to influencing factors such as crop choice, climatic patterns, irrigation technology and field-water management, land, and inputs including labor, fertilizer and machinery (Rosegrant et al., 2002; Kijne et al., 2002). Due to spatial variability in WP, several options exist for improving WP in agriculture at different scales. At plot and farm scales for example, options may involve combined research on plant physiology, agronomy and agricultural engineering that focuses on making transpiration more efficient or productive, reducing non-productive evaporation and making water application more precise and efficient (Molden et al., 2003). At irrigation system and basin scales, options may include reducing non-beneficial depletion, reallocating water among uses and tapping uncommitted outflows resulting in more output per unit of water consumed (Molden et al., 2003). As a result of climatic differences between locations, many options for improving WP need to be adapted to specific local conditions. However, local variation makes it difficult to upscale and downscale WP findings easily (Bouman, 2007). It is understood, though, that increased WP as a result of improved water management strategies at lower scales can result in either positive or negative linkages to WP at higher scales. For example, when low-value farm crops are supplied with the same amount of water that could supply high-value uses, overall productivity of basin supplies may be reduced when viewed in economic terms (Molden et al., 2003). Irrigation supply in many cases is used for multiple purposes. Failure to account for other uses of irrigation water has resulted in undervaluation of irrigation water, and by extension, of investments in irrigation infrastructure by water managers. Understanding the value of water in its alternative uses is essential for improving WP, and guides the management and allocation of water supplies among competing users (Renwick, 2001).

The river basin is a preferred unit of analysis for water resources management. Strategies for improved water management are now typically attuned to river basin scale. Seckler et al. (2003) argue that in a river basin where drainage from upstream users can be reused downstream, water losses occurring at lower scales are not true losses as long as they are or can be recovered and reused downstream. Although this argument has been useful in redefining the irrigation efficiency concept (Winchelns, 2002), which is important at basin scale in particular, it tends to downplay the importance of field-scale WP improvement interventions (Bouman, 2007). Reuse of water in many cases entails additional costs to users such as added cost to pump drain water, which many poor farmers can not afford (Hafez, 2003; Bouman, 2007), and reductions in water quality. Improvement of WP at lower levels is also important, since it can be directly translated to improved livelihoods of farmers (Mdemu et al., 2004). Wichelns (2002) further emphasizes that improvements in farm-level water management enhance the economic values generated with limited water resources even if measures of basin WP are within desirable ranges.

Many medium and small reservoirs in the UER in the Volta Basin display characteristics that are unique relative to common reservoirs during the dry season of the year, which justify strategies of WP improvements at plot or farm levels. Although at the peak of the rainy season these reservoirs conform to general characteristics of most conventional reservoirs in river catchments within the basin, they are generally closed systems with minimal or no surface water outflows downstream during the dry season. There is also typically little opportunity for water reuse downstream because most of the reservoir- irrigated schemes (with the exception of Tono and Vea) are small, and water is released to supply at most what is required by crops. Although the presence of large numbers of small reservoirs can impact the hydrology of the river basin, improving WP at field, farm or scheme scales under medium and small reservoirs in the UER may have positive impacts on the system as whole.

Definitions and frameworks of analysis for understanding WP exist (Molden, 1997; Bouman, 2007; Molden et al., 2003). Similarly, general principles underlying WP improvements and water saving at different spatial scales are elaborated (Molden et al., 2003 and Cook, 2006a; Guerra et al., 1998). However, these assumptions and principles are derived largely from studies conducted in Asia, and as such are not geographically applicable uniformly (Renwick, 2001; Molden et al., 2001; Dong et al., 2001; Singh, 2005). In particular, few such detailed studies have been conducted in the UER. Since current levels of WP in most medium and small reservoir irrigation systems are not well understood, it is difficult to determine at which level can WP be increased from improved water management practices. A clear understanding of WP at different spatial scales is important as a precondition to implementation of any improvement strategies. The current study therefore addresses this knowledge gap by providing WP analysis of the medium and small reservoirs inclusive of crop, livestock and fishery water uses at the local scale within the UER in the Volta Basin in Ghana.

1.2 Rationale of the study

The main objective of the GLOWA Volta Research Project (GVRP) is to develop scientifically sound decision support systems (DSS) for the assessment, sustainable use and development of water resources in the Volta Basin. Aspects of surface-atmosphere interactions as affected by climate change, land-use-change modeling, water use optimization and the integration of the different research components and simulation models into a DSS are being studied (GVRP, 1999 and 2002).

Under the water use and optimization research cluster in the GLOWA project, studies have been conducted relating to: groundwater recharge in semi arid-environments (Martin, 2006; Sandwidi, 2007), irrigation decisions under rainfall risk (Yilma, 2005), household water security and water demand (Osei-Asare, 2004), allocation of water resources for agricultural and economic development (Obeng-Asiedu, 2004), storage capacity and evaporation losses of small reservoirs (Liebe et al., 2005), and spatial-temporal patterns of rainfall (Friesen, 2002). Other important studies in the UER include determinants of success of community-based irrigation management (Gyasi, 2005), and performance and profitability of small reservoirs irrigation schemes (Faulkner, 2006).

While some of the studies (i.e., Obeng-Asiedu 2004; Faulkner, 2006) address subjects related to the content of the present study, they emphasize costs and benefits as well as tradeoffs and complementarities across water-using sectors at basin scale (Obeng-Asiedu, 2004) with limited application to local level decision-making processes. Faulker (2006) applies the concept of relative water supply to measure the performance of two small reservoir irrigated schemes, but does not include all surface and groundwater fluxes in water balance analysis, many of which are important for improved water management strategies at field or farm scales in semi-arid environments. The present study extends efforts on WP assessment of medium and small reservoirs and extends further the concept of WP assessment to livestock and fishery reservoir water uses in the study area.

1.3 Research objectives

The main objective of this study is to measure WP in medium and small reservoirs in the UER characterized by multiple uses of water. The specific objectives are:

1. To describe the multiple uses of reservoir water in the UER;
2. To estimate physical WP for dry season crop water use based on soil water balance analysis;

3. To estimate economic WP for crop, livestock and fishery water uses during the dry season;
4. To assess factors contributing to the value of water for dry season crop irrigation.

1.4 Outline of thesis

The thesis is organized into eight chapters. After a general introduction and problem statement in Chapter 1, Chapter 2 gives a general description of the study area. Chapter 3 describes the multiple uses of reservoir water in the UER with reference to the sample study reservoirs representative of medium and small reservoirs. In this chapter, aspects of reservoir water resources, dry season multiple water uses of the reservoir water, and management of reservoir water resources are explained. Chapter 4 describes the soil water balance and physical water productivity at field, farm and scheme scales. Chapter 5 contains an evaluation of the economic value of water for dry season tomato irrigation and Chapter 6 contains estimates of added values to reservoir water from livestock and fishery water uses. Chapter 7 assesses the factors contributing to the economic value of tomato irrigation during the dry season. Finally, Chapter 8 presents the conclusions and recommendations of the study.

2 STUDY AREA

2.1 Geographical location and administrative boundaries

This study was conducted in the Upper East Region (UER) of Ghana within the White Volta tributary to the Volta River Basin (Figure 2.1). The UER is located on the northeast corner of Ghana between latitudes 10°30' to 11°15' North and longitudes 0° to 1°30' West. It covers a land surface area of 8860 km^2 which is about 4% of the country (238534 km^2). The UER borders internationally with Burkina Faso to the north and Togo to the east and regionally with the Upper West and North Regions to the west and south, respectively. It is administratively divided into the six districts Bawku East and West, Bolgatanga, Bongo, Kassena-Nankana and Builsa. In 2005, Bolgatanga district was divided into three districts, the two new districts are Talensi-Nabdam and Garu-Tamparu. The regional capital is Bolgatanga.

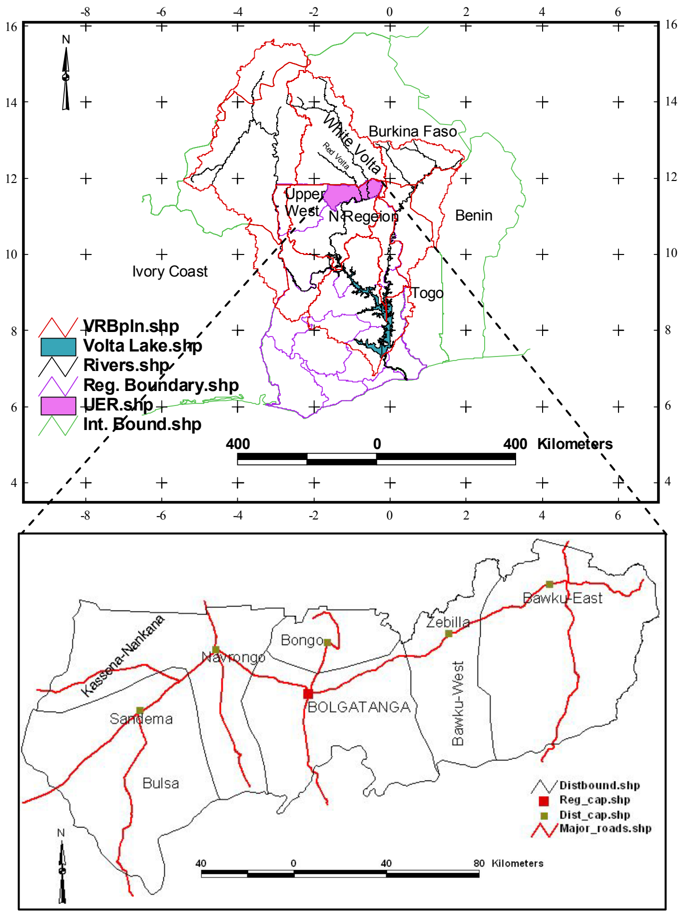

Figure 2.1: Location of the Upper East Region in the Volta River Basin (Source: Shape files from GLOWA Volta Database (GVD))

2.2 Climate

The climate of the region is influenced by the movement of two types of air masses: the harmattan and monsoon winds, which control the climate of the West African sub-region. The harmattan, or North East (NE) trade winds, originate from the Sahara desert and are characterized by dry and particle-laden air masses. The southwesterly (SW) monsoon winds carrying moist air from the Gulf of Guinea bring rains upon converging with the NE trade winds. Movement of the Intertropical Convergence Zone (ITCZ), where the two air masses meet, affects the climate of the savanna region, allowing more seasonal rainfall in the belt that lies south of the ITCZ (Kranjac-Berisavljevic et al., 1998).

The UER is characterized by a mono-modal rainy season starting in April-May and lasting into September or the beginning of October. Rainfall is erratic and spatially variable (Ditto, 1998). Average annual rainfall ranges between 700 and 1010 mm per year with peak rainfall occurring in late August or early September (Figure 2.2). More than 60% of the annual rain falls between July and September, with torrential rains generating high runoff due to the inability of the soils to absorb high intensity rains (Kranjac-Berisavljevic et al., 1998). Normally, precipitation in the region exceeds potential evapotranspiration only during the rainy (growing) season, while the opposite is true in the dry season. Annual potential evapotranspiration is estimated to be roughly double the annual precipitation. This translates into a necessity for utilization of water storage reservoirs to ensure availability of water for various uses in the dry season.

Temperatures in the region are consistently high, with the hottest month being March or April (40-45°C) and coolest month being August (26°C). Mean annual temperatures are around 28-29°C while the absolute minimum temperatures (15-18°C) occur in December. Relative humidity is generally higher during rainy season and decreases in the dry season. The region is generally characterized by low wind speed, varying between 0.4 and 2.5 m/s. Skies are generally clear during the months of October to November and February to May and cloudy throughout the rainy season between June and September. From December to January, skies are hazy due to suspended dust particles in the air carried by the easterly-south hamattan winds from the Sahara desert.

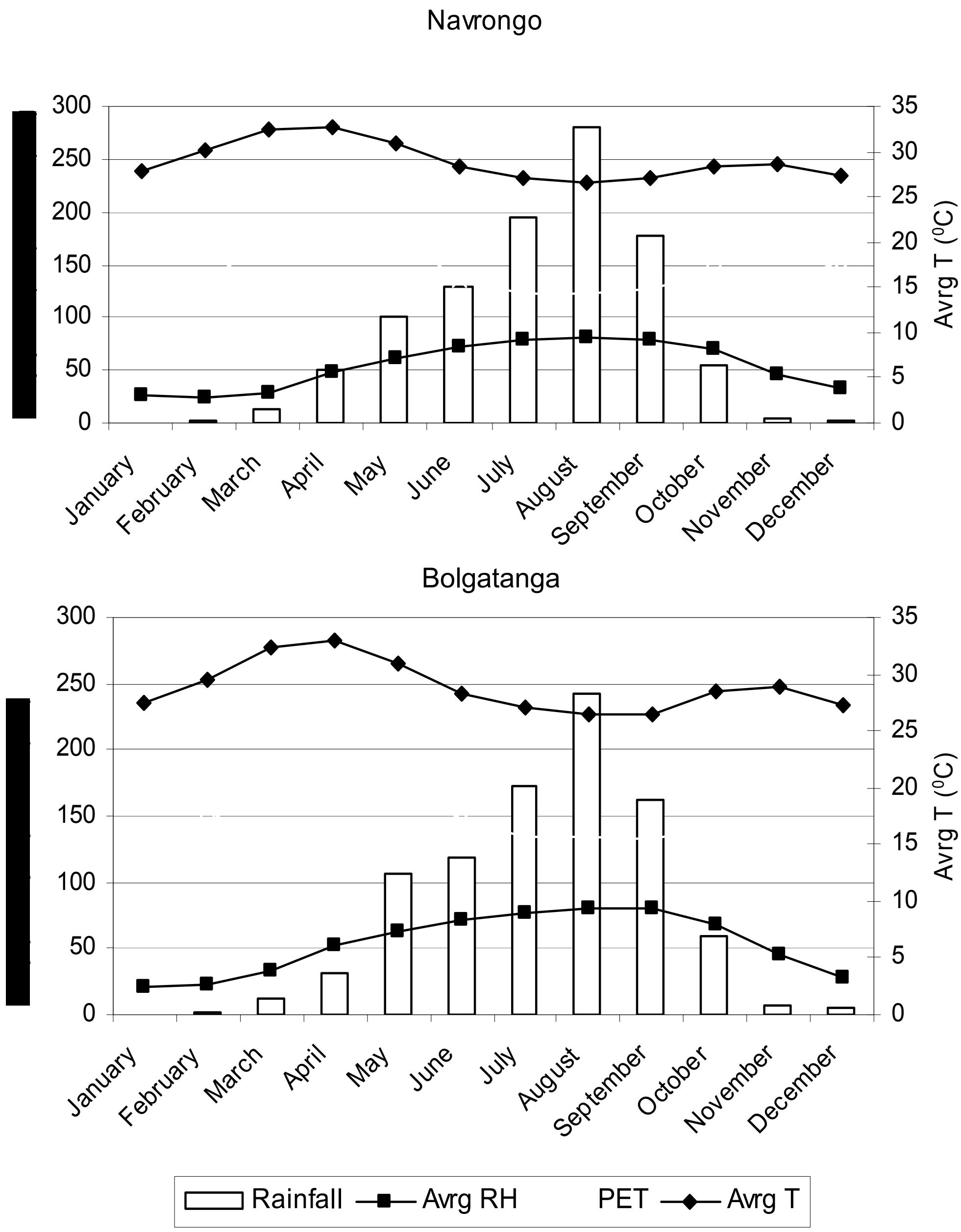

Figure 2.2: Long-term (1980-2005) monthly average rainfall, relative humidity (RH); potential evapotranspiration (PET) and temperature (T) for Navrongo and Bolgatanga weather stations (Data source: Ghana Meteorological Service).

2.3 Geology, soils and relief

The geological formations covering the Upper East Region are divided into three main groups, the Granitic, Voltaian, and Birrimian rocks. The pedology and the description of soil associations developed from these parent materials is discussed in detail by Adu

(1969). Generally, soils developed over granites cover large areas of the UER (Figure 2.3).

Gleyic and *Ferric Lixisols* cover large areas of the UER followed by *Haplic Lixisols* in the east and *Lithic Leptosols* in the southwest of the region. *Haplic Luvisols* cover the middle and the northeastern part of the region, while *Eutric Fluvisols* are found along the White Volta, in flood plains of the White Volta River (WVR), and in seasonal streams. The majority of soils in the UER are infertile, except soils occurring in seasonally flooded areas. This is typical of savanna zones, which have low accumulation of organic matter in the surface horizons owing to the high temperatures that cause rapid decomposition rates. The annual burning of the vegetation cover throughout the area also reduces the amount of organic matter in the soils (Boateng and Ayamga, 1992).

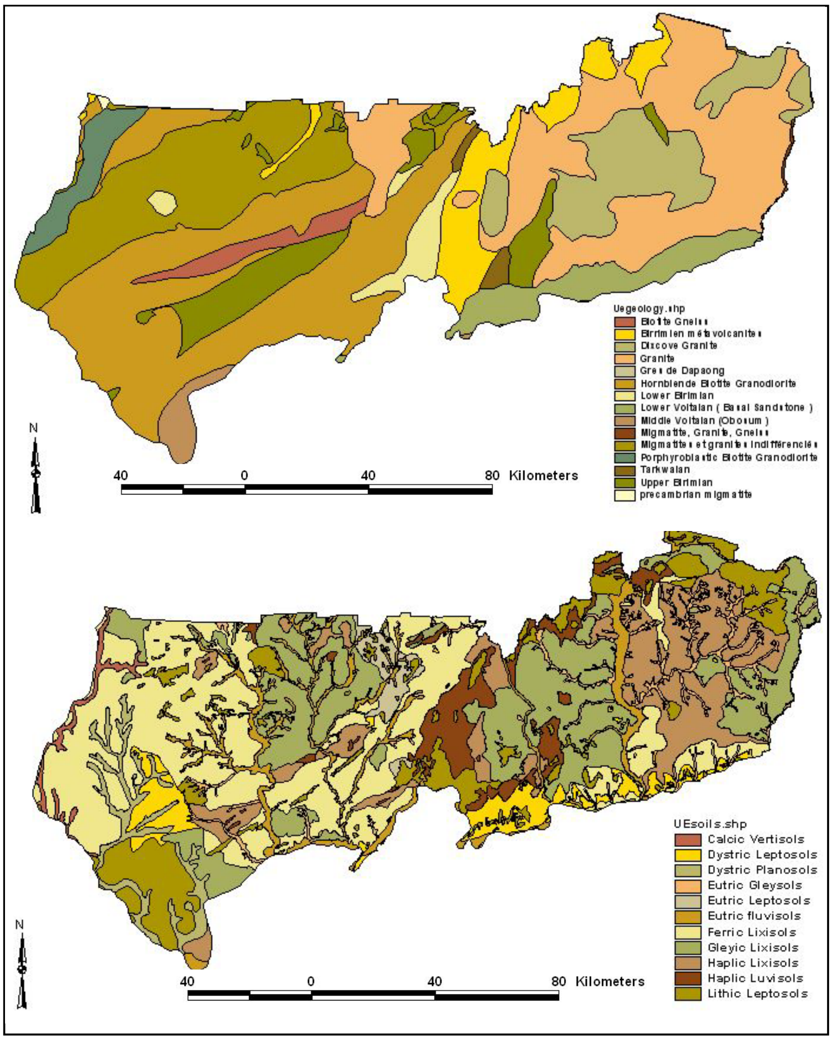

Figure 2.3: Geology and soils of the Upper East Region (Shape files data source: GVD)

Large areas of the UER are gently undulating with broad, poorly drained valleys and extensive flood plains adjacent to the Volta River (Kranjac-Berisavljevic et al., 1998). According to Adu (1969), the relief of the UER is related to the geology, where a range of Birrimian greenstone hills rising up to 457 m above sea level dominate north of Bawku and Zebilla along the border with Burkina Faso and in the southwest along the WVR. Areas occupied by granites are generally of low, gently rolling relief ranging from 122 m to 260 m above sea level. The relief under Voltain rocks has similar characteristics to granites, with few escarpments rising above 518 m near the border with Togo in the east. The mean elevation for the region is 197 m above sea level (Liebe, 2002).

2.4 Agro-Ecological Zones (AEZs), vegetation and land use

The UER belongs to the Guinea and Sudan Savanna Agro-Ecological Zones (AEZs) (Figure 2.4). The Guinea Savannah covers large parts of the UER in the western half and southern part of the region, while the Sudan Savannah covers the northeastern part. The Guinea Savannah AEZ has a growing period of 165 to 210 days with mean annual rainfall varying between 950 mm and 1500 mm. In the Sudan Savannah AEZ, the growing period ranges between 90 and 165 days, and annual precipitation varies from 550 mm to 900 mm. In both zones, the natural vegetation is characterized by open woodland savannas associated with perennial grasses in the southern and increasingly by annual tussock grasses in the northern zone (Windmeijer and Andriesse, 1993).

Crops and livestock form an important part of the mixed farming systems, and crop production is the major land use in the UER. Millet, sorghum, maize, bean and groundnuts are the main grain crops grown in upland areas during the rainy season. Rice is mainly grown on valley bottoms. Sorghum, groundnuts and millet are the main consumption food crops and play major roles in household food security. These crops can withstand moisture deficits during dry-spells within the growing season. Rice is an important crop for food and the market.Vegetables such as tomatoes, onions, pepper, and other leafy vegetables are produced in the dry season using irrigation at nearly all small and medium reservoirs in the UER. Rice and soybean are only irrigated in medium-sized reservoirs in the dry season. Livestock production is an integral part of the agricultural production system in the UER. Common livestock include cattle, goats, sheep and birds (chicken, fowls and ducks). Donkeys, pigs, rabbits, and dogs are also kept.

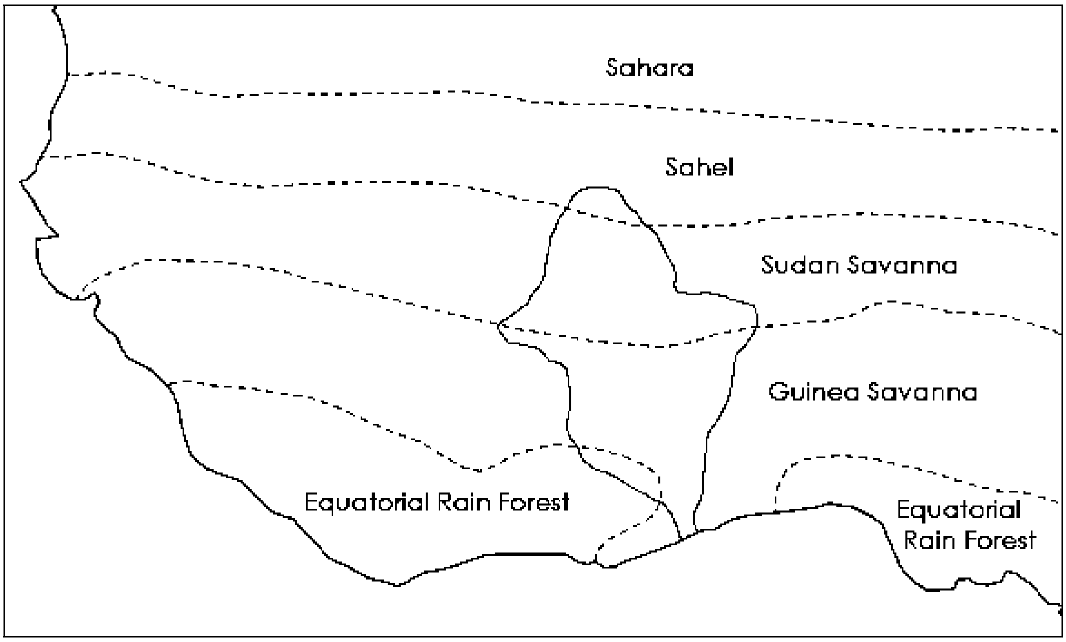

Figure 2.4: Agro-ecological zones in Ghana (Martin, 2005)

2.5 Drainage system

The UER is mainly drained by the WVR (Figure 2.5), with nearly all small and medium tributaries from various subcatchments in the northern segment of the region draining southward into the WVR. The drainage basin of the WVR within the UER starts from northeast along the border with Burkina Faso draining all areas along Bawku East and West down south. On the edges of the Gambaga escarpment, the WVR drainage turns southwest, separating the UER from the Northern Region. In the west, the region is drained by the Sisili River, which joins the WVR in the southwest corner of the UER. Areas between Bongo and Zebilla on the western side of the WVR are drained by the Red Volta River, which joins the WVR on the edges of the Gambaga escarpment as the WVR turns southwest. The areas north of Bolgatanga and large parts of Navrongo are drained by the Atankwidi subcatchment, while the Tono subcatchment drains areas northwest and west of Navrongo. All tributaries south of the WVR in the Gambaga escarpment drain southward away from the WVR (Liebe, 2002). Most of the subcatchments in the UER have developed inland valleys of different sizes and shapes. Small and medium-sized reservoirs have been constructed (Liebe, 2002) in these inland valleys to supply water for crop irrigation, livestock and domestic, fishery and other uses during the dry season.

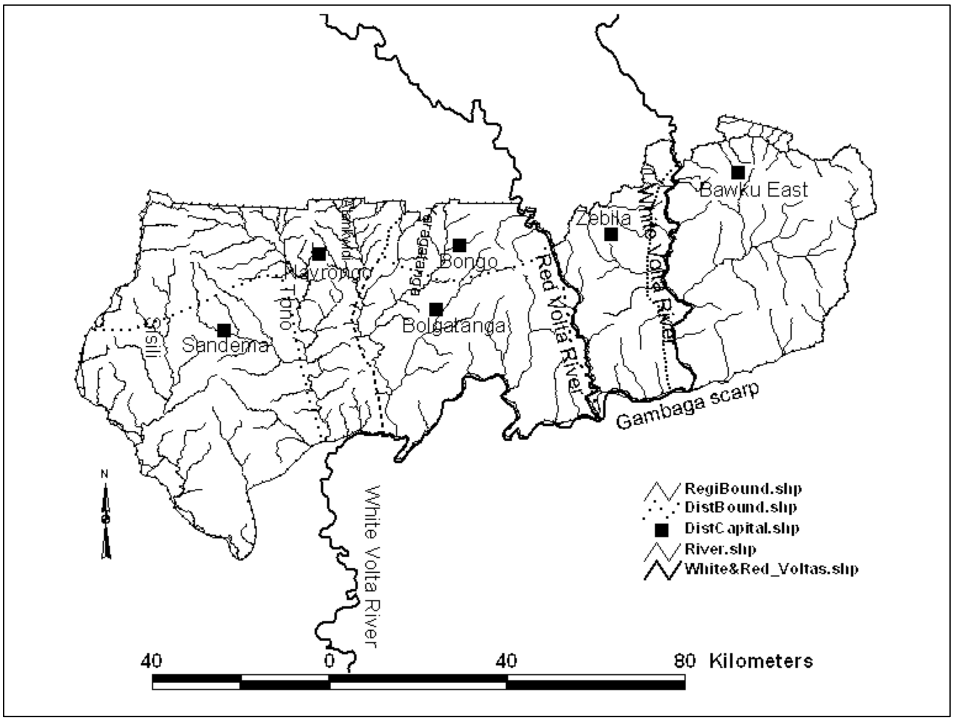

Figure 2.5: Drainage of the Upper East Region (Shape files data source: GVD)

2.6 Socioeconomic attributes

The UER is among the three poorest regions in Ghana. Agriculture employs above 80% of the population, making this sector key to socioeconomic growth for the region. To improve the difficult natural conditions in the Interior Savanna Zone (ISZ) of Ghana, the Ghanaian government, with assistance from foreign donors, developed ambitious irrigation schemes from the mid-1960s to the 1980s. It was apparently the belief of policy makers that such irrigation developments would replace indigenous soil and water conservation methods which, it was argued, could no longer cope with the pressures from an increasing population, environmental degradation and changes in climatic conditions (Kranjac-Berisavljevic et al., 1998). However, according to FAO (1968), irrigation schemes were constructed in order to bring the economy of the northern regions in line with that of southern regions of the country and to provide domestic substitutes for certain agricultural products imported during that time. The majority of these schemes, including Ghana’s largest irrigation schemes (Tono and Vea), are located in the UER where population density is high, i.e., about 118 persons per km^2, compared with national population density of 77 persons per km^2 (Bacho and Bonye, 2006), land is scarce and the incidence and depth of poverty is high (Gyasi, 2005). The irrigation schemes are vital for increasing food security and rural income by providing water for dry season farming, livestock and fishery, which are the main sources of cash income for rural households in the northern regions and the UER in particular (Gyasi, 2005). Food crops and high-value crops such as rice, onions, tomatoes, pepper, and traditional leaf vegetables are produced from the irrigation schemes in the area during the dry season.

2.7 Sample site selection and general description

Two study sites were identified for data collection: Tono and Dorongo, representing a medium and small reservoir irrigation scheme, respectively. Two main criteria were used for site selection. First, similar cropping patterns between schemes for comparison reasons, and second, a reasonable distance between sites to enable close field monitoring. At Tono, tomato and rice are the main dry season irrigated crops. These crops were allocated 100 ha each for the 2005/06 dry season. However, late in the season it was realized that the area under rice had increased to about five times the area under tomato. The reasons farmers shifted from tomato to rice in Tono were their unwillingness to risk crop failure due to tomato pests and diseases, a frequent occurrence for more than five years, and lack of capital, since tomato is considered capital intensive. Tomatoes, onions and leaf vegetables are common in most small reservoir schemes. Cropping patterns for small reservoirs in the UER consist of tomato at Bolgatanga, tomato-pepper at Navrongo, tomato-leaf vegetables at Bongo-Builsa, and onions at Bawku East-West. The Dorongo scheme at Bolgatanga was selected for study, since tomato is the main irrigated crop, allowing comparisons with Tono where irrigated tomatoes are also cultivated. The two sites are located about 40 km apart, enabling observations to be done at both sites on a daily basis.

2.7.1 Tono irrigation scheme

The Tono Irrigation Scheme is located at Navrongo in Kassena-Nankana District of the UER (Figure 2.7). The scheme was constructed between 1975 and 1985. The irrigation system of the scheme consists of a water storage dam with a maximum surface area of

1860 ha and storage volume of 93 MCM. The gross project area covers about 3860 ha of which 65% (i.e., 2490 ha) has been developed for irrigation. The catchment area, which collects the runoff for the storage dam, is 650 km^2. Canal and road networks with a total length of about 42 km and 120 km, respectively, are important parts of the infrastructure. The scheme is managed by the Irrigation Company of the Upper Region (ICOUR), a governmental parastatal managing large irrigation schemes (referred to as medium schemes in this study) including both Tono and the Vea scheme located at Bolgatanga.

The soils are developed over granites, primarily muscovites and hornblendes, and have light topsoils varying in texture from coarse sands to loams, and sub-soils varying from coarse sandy loams to clays with variable amounts of gravel (Boateng and Ayamga, 1992). Sandy clays and loams are located in valley bottoms. Good and very deep arable soils with good water holding capacity occur on alluvial flats on slopes of 2% or less. Generally, the soils are suitable for intensive mechanized irrigation farming of rice, other cereals, sugarcane, vegetables, tobacco, and fruits. Crops and vegetation (natural and artificial) are the major land covers within the scheme. Rice, soybean, millet, maize, tomatoes, groundnuts, cowpeas, and sorghum are the major crops. While rice and tomatoes are the main irrigated crops during the dry season, other crops are grown in the upland areas during the rainy season. The natural vegetation consists mainly of common savanna trees and grasses (Boateng and Ayamga, 1992). Artificial vegetation consists mainly of Eucalyptus trees, cashew nuts trees (*Anacardium occidentale*) and mango trees (*Mangifera indica L.*) planted in sparsely distributed plots. Natural and artificial vegetation cover land that is undeveloped for crop plots due to poor terrain, high presence of rock outcrops and/or soil scooped depressions created during scheme development.

2.7.2 Dorongo irrigation scheme

The Dorongo irrigation scheme is located about 3 km along the Bolgatanga-Sherigu road west of the Bolgatanga regional capital (Figure 2.6). The small reservoir and irrigation scheme were constructed in 1962 and rehabilitated between June 2002 and August 2003 under the Land Conservation and Smallholder Rehabilitation Project (LACOSREP) phase II project. The dam has an estimated storage capacity of about 0.24

MCM and a maximum surface area of 15 ha with a maximum depth of approximately 6 m at maximum flooding. The catchment area is about 112 ha and the total irrigable area of about 10 ha. The reservoir has a total infrastructural length of about 3.81 km for the dam wall and lined diversion canals. The reservoir is managed by a Water Users' Association (WUA) with about 150 registered members.

The soils consist of coarse sandy loams associated with hornblende or biotite granites with frequent stones occurring on the ground surface. They also consist of severely eroded and rocky valley sides with grey sandy loams and clays in valley bottoms. The soils are generally characterized by low water holding capacity, low subsoil permeability, shallow, low to moderate fertility and occasional to frequent rock outcrops limiting areas suitable for mechanical tillage. Slopes vary from 2-3%, and soils are considered suitable for cultivation of cereals, beans, nuts, and oilseeds (SRI, 1964). Crops such as millet, sorghum, groundnuts and maize form the major land cover and use during the rainy season. After rain-fed crop harvest, most of the land remains bare during the dry season after livestock have grazed crop residues except the area confined for irrigation using the reservoir water, which is mainly used for tomatoes.

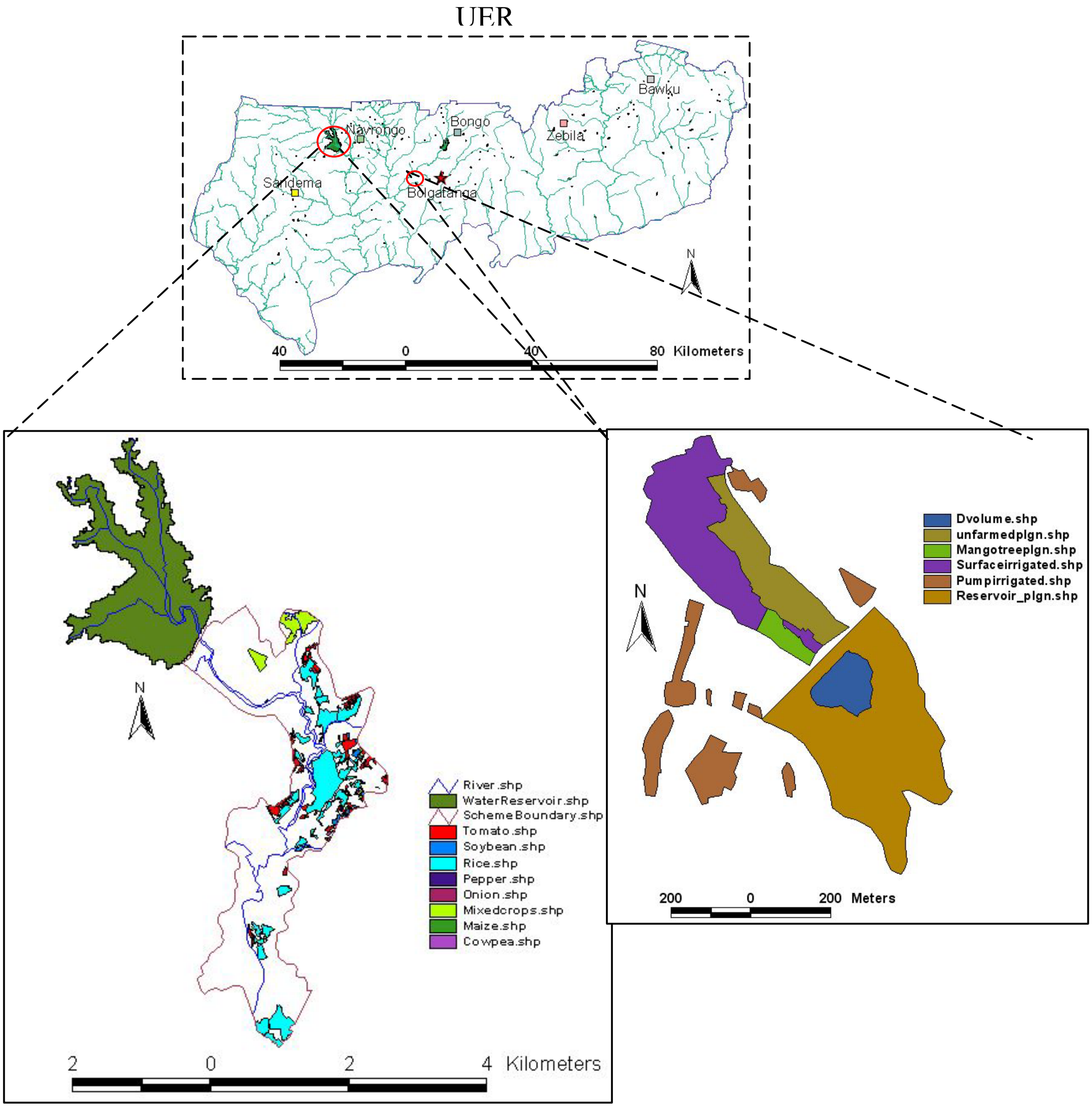

Figure 2.6: Tono and Dorongo case study schemes (Shape files data source: GPS survey and GVD)

3 MULTIPLE USE OF RESERVOIR WATER

3.1 Introduction

There is a growing interest in closer examining water sources that supply multiple uses as a means of improving water resources planning and management. However, the nature and extent of multiple water uses is typically neither documented nor understood. Even before the advent of piped water supply, people, livestock and the physical environment commonly shared various sources of water, such as natural rivers, lakes and reservoirs, for drinking, cooking, sanitation, livestock watering, and construction purposes. This long-standing practice of sharing sources of water is still common in many places in the developing world. Population growth that stretches per-capita available water resources in water-scarce countries has necessitated attempts to achieve a balance among water uses, especially those that would have been otherwise neglected because of the perception that certain users or uses are important and others less so.

Multiple water-use systems are considered to be more efficient when the value of water from other uses that were not considered during planning and design are subsequently incorporated in current planning and performance assessments. This is particularly true in the irrigation sector, which usually supplies many other uses (Bakker and Matsuno, 2001; Gowing et al., 2004; Boelee and Laamrani, 2003; Meinzen-Dick; Van der Hoek, 2001). In some irrigation systems, non-crop water use exceeding 50% of the irrigation supply has been reported (Renault and Montginoul, 2003). In Northern Morocco, Boelee and Laamrani (2003) found water being directed from the main irrigation canal into underground house storage tanks via small canals, or by pump to provide water for various purposes such as drinking and cooking, watering livestock, laundry and brick making. As a result of observed multiple water uses from irrigation systems, the common perception that irrigation systems supply water only to field crops is changing (Gowing et al., 2004; Meinzen-dick and van der Hoek, 2001; Bakker and Matsuno, 2001).

Failure to take into account the multiple use aspects of irrigation systems has two major consequences: first, water stored and controlled within irrigation systems and the entire return on investment in irrigation and related infrastructure has been undervalued (Bhattarai et al., 2003; Bakker and Matsuno, 2001) and second, because of such undervaluation, when water scarcity increases in some countries, water is re-allocated from irrigation to more beneficial water sectors such as municipal, industrial or environmental maintenance purposes (Meinzen-Dick and Van der Hoek, 2001). Undervaluation of irrigation water can be remedied by assessing the full range of benefits from multiple use systems, and by internalizing multiple water use aspects during planning of irrigation systems. However, management complications resulting from positive externalities associated with multiple water use cannot be ignored (Renault and Montiginoul, 2003). The Multiple Use System (MUS) project, a CGIAR-Challenge Program for Water and Food (de Vries et al., 2006) is designed as a response to failures in planning and management of multiple use water resources systems.

Apart from the multiple uses of water practiced in large irrigation systems, which are widely documented (Meinzen-Dick and Bakker, 2001, Li et al., 2005, Going et al., 2004, Renwick, 2001), medium and small water reservoirs also provide multiple services. These systems, spatially distributed in the semi-arid regions of SSA, provide water for multiple uses in ways that balance the livelihood interests of competing users, including irrigation, livestock watering, fisheries, domestic uses and other water-related enterprises such as brick making. The medium and small reservoirs, unlike other types of multiple use systems, have a unique feature: a storage facility for capturing runoff during the rainy season for use during the dry season thus acting as closed surface water systems with little or no surface outflows downstream. This type of multiple water use system is not adequately described in existing literature. This study, therefore, documents the multiple water uses with reference to medium and small reservoirs in the UER.

3.2 Reservoir water resources in UER

Water reservoirs in the UER are spatially distributed according to topographic controls within the region. More reservoirs are located in the eastern half of the region (Figure 3.1) and fewer in the western half. The eastern half, which mainly lies above the regional mean elevation, is characterized by drainage boundaries that fold back and forth (Liebe, et al. 2005) providing favorable conditions for reservoir construction.

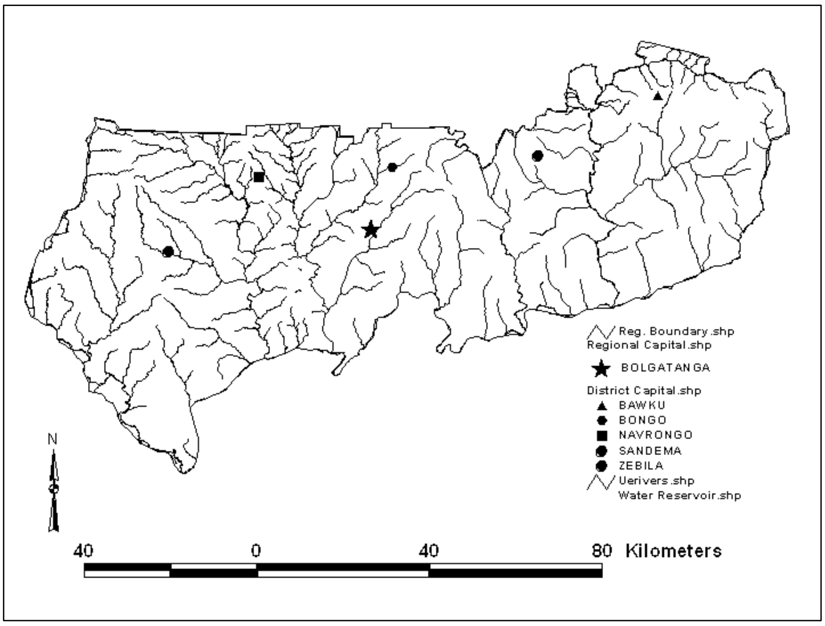

Figure 3.1: Distribution of small reservoirs with respect to Upper East Region topography (Shape files data source: GVD)

Currently, there are about 156 reservoirs in the UER with an estimated total surface area of 3329 ha. Seventy percent (70%) of this area is contributed by the medium reservoirs, Tono (1894 ha) and Vea (435 ha). Small reservoirs, managed primarily by WUA and ranging from 1 to 35ha in size, contribute the remaining 30%. At full storage capacities, 293 MCM (Liebe et al., 2005; ICOUR, 1995) of water can be captured during the rainy season. However, the reservoir storage volume decreases gradually due to abstraction, evaporation and other outflow components from maximum storage at the end of the rainy season to minimum or zero storage between February and May, depending on the size of and demands for reservoir water.

3.3 Dry season multiple uses of water reservoirs

Reservoirs in the UER were developed mainly to provide water for irrigation in order to increase food crop production, and to supply water for human and livestock needs. Increased coverage of potable water supply via portable pipe or pumped boreholes in many rural areas of the UER has created the opportunity for fishery water use within the reservoirs, thus designating irrigation, livestock and fishery as the three important uses of reservoir water resources in the region.

3.3.1 Irrigation water use

Water use for agriculture constitutes a large percentage of overall reservoir water use in both medium and small reservoirs. In medium reservoirs, water is used for irrigating rice, soybean, tomatoes, onions, pepper and other leaf vegetables such as cucumber, garden eggs, okra, and kenaf (Figure 3.2). Other crops, particularly in Tono, include perennial crops such as mango trees which are sparsely distributed in marginal areas within the project scheme. Tree crops other than fruit production are important for providing shade to farmers during the period of high temperatures from February to April. Non-traditional crops such as cocoyam and sugarcane are also found in marginal areas.

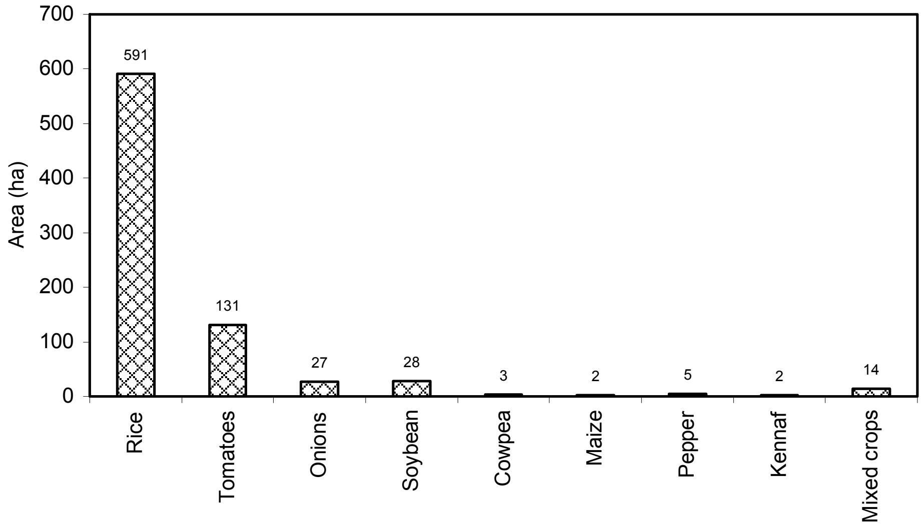

Figure 3.2: Dry season cropped area at Tono irrigation project (2005/06) (Data source: Own survey)

In the small reservoirs, four cropping patterns are common (Figure 3.3): 1) tomatoes are the major crop and onions, pepper, and leaf vegetables the minor crops at Bolgatanga, 2) at Bongo-Builsa the major crops are tomatoes-leaf vegetables and onions and pepper are minor, 3) tomatoes and pepper are the major crops with onion and leaf vegetables as minor at Kassena-Nankana, and 4) at Bawku East-West, onions are the major crop, and the remaining crops the minor. However, due to an increase in diseases affecting tomatoes in Bolgatanga and Kassena-Nankana, and increased emphasis by the Ministry of Food and Agriculture (MOFA) on shifting cropping patterns, a stronger focus on onions is expected in the future, given that environmental conditions are similar to those found in Bawku East-West, where onions are produced extensively. The described cropping patterns reflect, among other factors, the different mechanisms used to supply water during irrigating (Table 3.1).

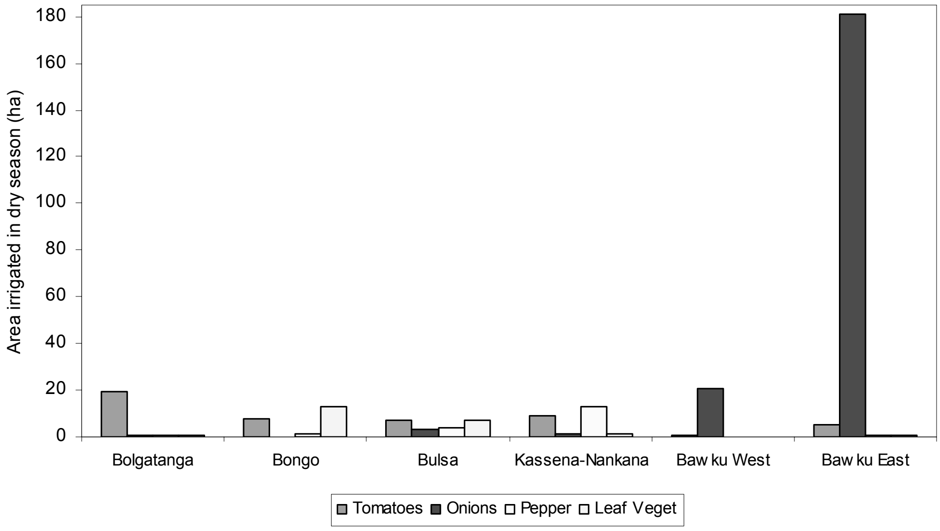

Figure 3.3: Average dry season crop acreage for small reservoirs in the UER (2000/01-2002/03) (Data source: MOFA Bolgatanga, 2005)

Table 3.1: Irrigation water use practices in medium and small reservoirs

Medium reservoirs	**Small reservoirs**
• Plots are supplied with irrigation water from field canals (laterals).	• Plots are supplied with irrigation water from laterals or sub-laterals.
• Furrows between the ridges for crops like tomatoes, soy bean and cowpea are flooded	• Furrows between the ridges for crops like tomatoes flooded.
• Small beds are used for onions, water is ponded in the furrows separating the beds and bowls are used to fetch water to sprinkle on top of the beds. o Labor intensive but more water efficient than the former, which leads to surface water losses.	• Small beds are used for onions, water is ponded in the furrows separating the beds and bowls are used to fetch water and sprinkle on top of the bed.
• Similar practices apply to leaf vegetables such as cucumber, kenaf when they are grown on small beds and are not intercropped.	• Similar practices apply to leaf vegetables such as cucumber, kenaf when they are grown on small beds and are not intercropped.
• Pump irrigation is practiced along the main drains by pumping drain water to irrigate adjacent areas.	• Pump irrigation is practiced by pumping water directly from the dam to irrigate plots outside the garden area (designed irrigation area).
• Continuous or intermittent flooding is applied on lowland rice fields.	• No rice grown in dry season.

3.3.2 Livestock water use

Livestock watering in medium reservoirs is done from the main reservoir, primary canals and secondary canals. Livestock watering in the secondary canals is practiced only when there are no cropped plots adjacent to the canals, as livestock, particularly cattle, goats, sheep and donkey, are grazed on fallow plots. Whereas the impacts of livestock watering such as physical damage and water pollution due to livestock droppings, tramping and urine are not felt on the main dam because of its large size, damage can be seen on primary and secondary canals caused by livestock struggling to access water directly from the canals. Livestock are also watered from farm and main drains in medium reservoirs. In small reservoirs, livestock watering is confined to the main reservoir, and few cases of watering from irrigation canals can be observed because the water flows in the laterals or canals during irrigation events only. However, few incidences of livestock watering in canals and main drains can be observed in some of the small reservoirs that have relatively longer-duration irrigation events (more than 3 hrs). Thorough livestock watering in irrigation canals, irrigation infrastructure can be destroyed and crops damaged, which can have negative consequences for the general socioeconomic condition of the community. Table 3.2 shows the differences in terms of water access points and general water quality aspects between medium and small reservoirs.

Table 3.2: Livestock watering practices in medium and small reservoirs in UER, Ghana

Medium reservoirs	Small reservoirs
• Livestock from the communities around the reservoir get access to water directly in the reservoir.	• Livestock access water directly from the reservoir.
• Livestock from communities along main canals and drainage systems get access to water from the canals and drains. o Continuous stepping of livestock into the canals when accessing drinking water damages the canals.	• On few occasions livestock can access water from canals. o Water is available in canals during irrigation events only (1-5 hrs)
• Water quality due to livestock droppings is not a serious problem because of the large volumes of water.	• As the volume of water decreases in the reservoir, water quality becomes constrained for uses such as bathing and cloth washing because of turbidity due to livestock trampling and droppings.

3.3.3 Fishery water use

Although major fishery activities at medium reservoirs are carried out within the main reservoir (Table 3.3), considerable activities take place within the primary canals, secondary water storages along primary canals, and in the main river stream that drains the entire project area. While fishing in the main reservoir involves the use of major fishing gear, including canoes and fishing nets, simple fishing gear such as trap nets and fish hooks are commonly employed in the canals and secondary water storages in the project area. During the development of the Tono and Vea irrigation reservoirs, a fish aquaculture component was incorporated in the form of fish ponds of 4.8 ha and 3.2 ha, respectively. However, the ponds collapsed because of management problems, although plans are underway to revive fish farming, and some of the fish ponds in Tono have been leased to a private investor.

In most small reservoirs, fishing activities are confined within the reservoirs themselves, with a small number of fish being trapped in the release-valve boxes, which are normally checked after the valve is closed at the end of each irrigation event. Within the reservoir, fishermen use trap nets and fish hooks as their main fishing gear. Very few fishermen use fishing canoes.

Table 3.3: Fishing practices in medium and small reservoirs, UER, Ghana

Medium reservoirs	**Small reservoirs**
• Fishing done in o main reservoir; o primary canals; o secondary recharge storages in canals; o drainage streams; o Tono River main drain.	• Fishing done in o main reservoir; o diversion boxes after irrigation events.
• Fishing canoes and nets are the main fishing gear in the main reservoir. • Set and wait nets, fish traps and fish hooks are common in main canals and main drains.	• Set and wait nets and fish hooks are main fishing gear in the main reservoirs.

3.3.4 Other water uses

In medium reservoirs, domestic water use (cooking, drinking, sanitation, and house construction) is very common for communities living along the secondary canals and surrounding the reservoirs. People from distant communities, whose farming activities take place within the project, use the canal water for cloth washing and body sanitation.

Bathing and cloth washing are normally done in flowing water within the canal or along the edges of canals. Domestic water use in the communities through which the primary canal passes, particularly in Tono, was taken into account during the design of the canals, and steps are provided at some locations along the primary canal so that water can be accessed even at low flow levels. For house construction purposes, water containers are commonly used to fetch water from the canal and carried to the construction site, either on the head or using pull-carts with donkeys. In small reservoirs, a similar typology of domestic water use (Table 3.4) is observed, with the only difference being that water is drawn from the reservoir, or bathing and cloth washing are carried out in the water body behind the dam.

Table 3.4: Other water use in medium and small reservoirs

	Medium reservoirs	Small reservoirs
Domestic use	• Communities around the water bodies depend on reservoir and canal water for cooking purposes • Washing of cloth and bathing are carried both in the main reservoir and irrigation canals. In few occasions buckets are used to fetch water and wash at short distances from the water body • Quite often drainage from washing flows back into the main water body.	• Boreholes are mainly used to supply water for cooking purposes • Washing of cloth and bathing are done mainly from the main reservoir. Sometime buckets are used to fetch water and wash a short distance from the main reservoir. • Quite often drainage from washing flows back into the main water body.
House construction enterprises	• Water is collected from the dam or main canals using pull/push carts or carried by head to the construction sites • Bricks are sometimes manufactured near the main canals and later carried to the desired destination when dried.	• Water is collected from the dam using pull/push carts or carried by head to the construction site. • Deposited sediments in the dam are sometimes used to manufacture bricks when water in the dam is almost completely drawn down. o desilting mechanism o serious scouring can increase percolation losses
Environment	• The water body in the main reservoir, canals, drainage systems and recharge storages provides favorable environment for water body ecosystems including fish, crocodiles, ducks and water birds.	• Water body in the main reservoirs create favorable habitat for water body ecosystems including fish, crocodiles, and water birds

3.4 Land Tenure in the UER

The majority of lands in the UER are under a customary land tenure system. The land is entrusted to the '*tendana*', literally meaning the owner of the land (Kasanga, 1995) who is the custodian. The '*tendana*' is normally the patrilineal descendant of the first family to settle in the area (Gyasi, 2005 and Kasanga, 1995). Tendamba (plural of 'tendana') are spiritual caretakers of land resources and grant usufruct customary rights to community members for free, although ownership rights continue to be vested in the community preventing the granted land from being disposed of by the allocated families (Gyasi, 2005). However each family's land is secure and controlled by families as long it is used for what it was allocated for. Although a similar land tenure system is applied for irrigated lands, two types of arrangements for land ownership exist: a secure tenure wherein users of irrigation facilities have total control over the command area, and seasonal tenureship, common in most small reservoir schemes managed by WUA, whereby land is returned to the original landowning families in the rainy season (Gyasi, 2005). In medium reservoirs, land is owned by the agency managing the schemes, although communities are involved in allocating plots to their farmers from the blocks of farms allocated to the community by the project management (section 3.5.1).

3.5 Management of reservoir water resources

The Ghanaian Water Resources Commission (WRC) Act (1996) specifies that ownership and control of all water resources are vested in the President on behalf of the people, and designates the WRC as the body with overall responsibility for water resources management in Ghana (Water Front, 2004). The WRC plans and regulates water resources development in co-operation with local government and planning authorities. Most of the important government agencies involved in water resources management and development, such as Ghana Irrigation Development Authority (GIDA), are represented on the Commission. Other institutions represented on the commission include: Ghana Water Company Limited which is responsible for portable water, the Hydrological Services Department, Volta River Authority, Water Research Institute, Meteorological Services Department, Environmental Protection Agency, Forestry Commission, and Minerals Commission (Water Front, 2004). The WRC is responsible for the initiation, control and coordination activities connected with development and utilization of water resources and the granting of water rights. Granting of water rights is seen as the main instrument to regulate water resources use (Water Front, 2004).

3.5.1 Medium reservoirs

The management of medium irrigation reservoirs in the UER, i.e. Tono and Vea, is the responsibility of ICOUR, a semi-autonomous government agency that provides services to small-holder farmers within the two projects. Participating communities or project villages under ICOUR are organized into irrigators' associations or village committees (VCs) whose functions, include land allocation at the village or community level. The village committees elect representatives who act as links between ICOUR management and VCs. The VCs are represented at various ICOUR meetings relating to decisions on operation and management of the schemes, and irrigation levy decisions.

An ICOUR consultative meeting is held to reach a consensus on, among other things, the irrigation levy at the start of dry season for different crops (Figure 3.4). This levy is charged on a per-hectare basis, and is crop specific. For the VCs to be allocated land, they have to raise and deposit their contributions at the ICOUR project office, and in turn the project manager allocates land consistent with the deposited contributions. The VCs then distribute the land to community members on the basis of each farmer's contribution. The remaining project area (not allocated to VCs) is contracted to anyone from the region (contract farmers) willing to farm in the project upon payment of a water levy consistent with that paid by VCs.

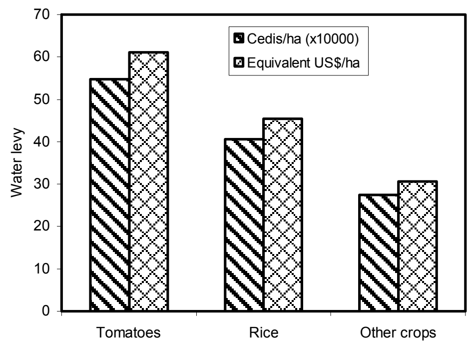

Figure 3.4: Irrigation levy for 2005/06 dry season at Tono (Source: ICOUR consultative meeting, October 2005, Exchange rate, 1 US$ = 8960 cedis as of Nov 2005, Barclays Bank, Ghana).

Although it is believed that the participation of VCs enables ICOUR to deal collectively with the farmers efficiently, and perform its managerial activities smoothly (Gyasi, 2005), nevertheless there are problems associated with farmers' participation in the project areas which, negatively impact reservoir water resources management. For example, allocation of water at tertiary canals was ideally supposed to be performed by VCs. This arrangement proved to be difficult due to violation of water allocation timetables. A shortage of project irrigation officers makes proper water allocation on farm laterals nearly impossible, so that during the irrigation season the gates of farm laterals are often opened even when there are no farmers using the water in some of the laterals. As a result, some farmers have been able to irrigate without paying water levies as required by the project management. This not only discourages farmers who abide by the project tenancy agreement, but encourages inefficient use of water resources. Laxity in water supply allocation that does not reflect crop irrigation water requirements have encouraged many farmers to farm on previously uncultivated lands, commonly known as waste lands, which were not fully developed during project development, without paying water levies. These so-called waste lands have expanded in area in a manner comparable with obvious increases in crop water requirements.

3.5.2 Small reservoirs

The Land Conservation and Small Reservoir Rehabilitation Project (LACOSREP), during its first and second phase of operation in the UER, included elements of the Water Users' Association (WUA) as an important strategy for the sustainability of rehabilitated small reservoirs upon project completion and the handing over of rehabilitated reservoirs to beneficiary communities. The formation or prior existence of a functional WUA was in fact a prerequisite for a given community to have its dam rehabilitated. Currently, nearly all rehabilitated small reservoirs are managed under WUAs. A typical WUA consists of a chairman, secretary and a treasurer. The WUA is an umbrella organization that encompasses affiliated groups in the beneficiary community that have stakes in the dam infrastructure and services, and which organize economic interests (Gyasi, 2005). Irrigators, livestock keepers and fishermen are the main economic interest groups, which organize themselves into associations whose representatives constitute the WUA's executive, referred to as Damsite Management Committee (DMC).

WUAs are charged with the overall responsibility for managing the small reservoirs. Their responsibilities include maintenance of dam infrastructure, land allocation, collection of water levies, formulation and enforcement of by-laws, and general administration related to the reservoirs. The DMC, together with the community members, agree on the water levy at the beginning of the season. The levy is a fixed sum, identical for every participating farmer in the community. Livestock keepers and fishermen who are members of the WUA also contribute to the main WUAs. The WUA's contributions are used for repairs and maintenance of irrigation canals, dam walls, valves and spillways. The Ghana Irrigation Development Authority is in principal required to provide technical personnel to support WUAs in management of the small reservoirs when the need arises.

3.6 Constraints and potential for improving reservoir water resources management

3.6.1 Medium reservoirs

The presence of reliable records on the operation of a reservoir can greatly facilitate the planning of water supplies for various demands. Irrigation, the largest user of water reservoirs, certainly plays a key role in guiding the planning of reservoir operations. The presence of deteriorated water conveyance infrastructure, which can no longer properly retain water, thus making control of water a difficult task, is a major constraint to improved reservoir water resources management.

Inadequacy of irrigation water management personnel is also a constraint to the management of reservoir water resources. For example, an increased number of irrigation technicians could easily facilitate improved water allocation to irrigated farms depending on the water demand of the cropped fields. Reliance on VCs for water allocation has been shown to be unpractical, because it is difficult for VC members to deny water to fellow farmers who have not paid water levies. Additionally, the existence of free-flowing water throughout the system (even in uncultivated plots) due to deteriorated canals makes it difficult for farmers to resist using it. Nevertheless, opportunities exist for improving management. Rehabilitation of irrigation infrastructure could be one of the long-term solutions for efficient reservoir water resources management. Concentrating farmers in a few selected plots could be considered as a short term solution, and could substantially reduce water loss and irrigation water requirement. This is in contrast to the current practice whereby farmers' plots are scattered throughout the entire project area, limiting the water supply through conveyance losses. The use of project extensionists to provide assistance in water allocation is another short-term solution. An increase in the number of water management personnel at lower levels can help to ease the problems associated with poor water allocation.

3.6.2 Small reservoirs

Small catchment sizes combined with unreliable rainfall is a constraint for the efficient utilization of small reservoirs. This results in generation of insufficient runoff, which may cause water shortages at the end of the dry season. Water leakage during the rainy season before the irrigated farming season starts when the hydraulic head in the reservoir is high, is also a problem. Provision of support by GIDA for planning dry season water-use activities, especially identification of an appropriate area to be irrigated in relation to available water in the reservoir, could help avoid water deficits before crop harvests. Additional water harvesting wherever possible, by directing runoff from nearby sub-catchments to the dam, could provide a solution to the water shortage caused by small catchment size and unreliable rainfall.

3.7 Summary and conclusions

Water reservoirs are important for socioeconomic development in the UER, without which the livelihood of many communities would be jeopardized. These reservoirs provide water for many uses, ranging from irrigation, livestock watering and fisheries to domestic uses such as cloth washing, bathing, and general construction. The first three are the most important with respect to the volume of reservoir water use, and irrigation is the major reservoir water user.

The ICOUR and WUAs are responsible for the management of water in medium and small reservoirs, respectively. The water levy, charged on the basis of the relative size of plots of land allocated to participating farmers, is used in part to meet the operation and maintenance costs of the schemes. The levy is regarded as an incentive to more responsible use of water, although in certain cases, payments of water levies by farmers have been translated into rights of over- and mis-use of water. This translation is not widely observed in the UER, although there are isolated incidents of water mis-use, particularly in medium reservoirs where water supplies are comparably higher than in small reservoirs.

Deteriorated water conveyance infrastructure is a constraint to sustainable reservoir water resources management. This is aggravated by inadequate of water management personnel in medium reservoirs. Rehabilitation of irrigation infrastructure, together with changing management strategies in medium reservoirs, hold the potential for improving reservoir water resources management. Insufficient catchment size is a problem at some small reservoirs, resulting in low and uncertain runoff generation. Support by MOFA for planning dry season water-use of small reservoirs, particularly the matching of available water to crop demand, will help farmers to avoid water deficits occurring before crop harvesting. Runoff harvesting from nearby catchments could also help to substantially increase the volume of reservoir water during the rain season.

4 SOIL WATER BALANCE AND PHYSICAL WATER PRODUCTIVITY

4.1 Introduction

Improving water productivity (WP) is one important strategy for meeting future water scarcity, which is driven particularly by population growth and, potentially, by climate and land-use change. Improving WP in agriculture will reduce competition for scarce water resources, mitigate environmental degradation, and enhance food security, simply because producing more food with less water makes more water available for other natural and human uses (Rijbersman, 2001). To emphasise the importance of WP, Molden et al. (2001) contend that an increase of WP in agriculture by 40% globally may reduce the amount of additional freshwater withdrawals needed to feed the world's growing population to zero. How, when, and where such a breakthrough could be realized is currently uncertain. However, it remains clear that WP improvement is a critical condition for sustained human development (UNDP, 2006).

Water productivity can be defined at different spatial scales such as plant, field, farm, scheme, sub-basin, and basin or regional scales. The effective identification of the unit under definition is the basic requirement in WP assessments. Increasing spatial scales of WP analysis requires consideration of different water flow pathways. For example, at scheme level, some of the water would be depleted by means other than evapotranspiration, such as deep percolation, commonly accounted for as losses. However, it is also difficult to ascertain how much of the deep percolation appears in groundwater systems available for subsequent uses, and thus not necessarily counted as loss. The situation becomes more difficult at large spatial scales such as river basin because of complicated water pathways with increasing scale of analysis.

Different WP performance indices, referred to as WP indicators (Cook et al., 2006a) are used to gage the WP of a system under definition. For example, physical crop WP can be calculated based on crop yield in terms of transpiration (WP_T), evapotranspiration (WP_{ET}), or amount of irrigation water supplied (WP_I). WP_T is relevant at field scale although practically it is not possible to separate transpiration from evaporation. Since transpiration is the only water flux in an agricultural field actually passing through the crop, WP_T is referred to as consumptive WP (Bouman, 2007). WP_{ET} has fundamental relevance in agricultural production and is valid to any scale (Molden et al., 2003). Evapotranspiration is a depletive use that renders water unavailable at another spatial scale (Bouman, 2007). Other water productivity indicators defined in terms of available water, depleted water, beneficially depleted water, and process depleted water have been used to reflect options for improved water management (Cook et al., 2006a, Molden et al., 2001). According to Cook et al. (2006b), estimates of WP have two basic uses: firstly, as diagnostic tools to identify the level of water-use efficiency of a system under study and secondly, to provide insight into the opportunities for better water management towards increased WP at the scale under consideration.

Inspite of the fact that an understanding of WP is a prerequisite for improvement strategies, little is known concerning emperical WP for reservoir-irrigated systems of the UER. To address this problem, a soil water balance analysis was conducted to assess water use and WP for the 2005/06 dry season irrigated crops at field (plot), farm and scheme levels for two sites (medium and small reservoir) in the UER of Ghana. The main objective of this study is to develop soil water balances used to estimate physical WP for dry season crop-water use. Simulation using the Soil-Water-Atmosphere-Plant (SWAP) model was utilized to assess the soil water balance and WP at field scale. Conventional soil water balance analysis was applied at farm and scheme scales.

4.2 Methodology

4.2.1 Soil water balance and physical WP at field level: SWAP Simulation

SWAP Model

SWAP is an agro-hydrological model for integrated modeling of the soil-water-atmosphere-plant continuum (Figure 4.1). The model simulates transport of water, solutes and heat in variably saturated soils. In this study, only the water transport simulation module is applied to simulate soil water balance at field scale.

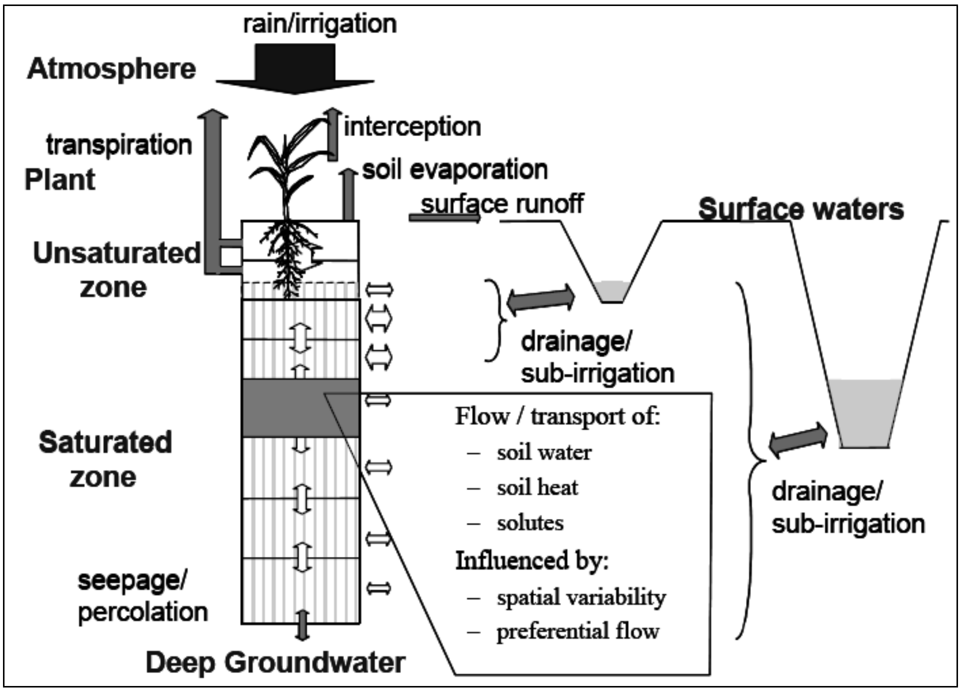

Figure 4.1: Schematization of hydrological process involved in SWAP (van Dam, 1997)

The model boundary conditions are defined by soil surface with or without a crop and the atmospheric conditions at the top (soil or canopy), surface water interactions, unsaturated zone or the upper part of the groundwater at the bottom boundary. For a cropped top, simulation can be implemented under simple or detailed crop modules. In this study, the simple crop module is applied.

Soil water flow

Assuming one-directional vertical flow, SWAP solves Richards equation (Eq. 4.1) numerically subject to specified initial boundary conditions and with known relationships between soil hydraulic variables, i.e., soil moisture (θ), pressure head (h) and hydraulic conductivity (K):

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial\left[K(h)\left(\frac{\partial h}{\partial Z}+1\right)\right]}{\partial Z} - S_a(h) \tag{4.1}$$

Where: C is the differential soil water capacity [cm^{-1}], h is the soil water pressure head [cm], K is the hydraulic conductivity [cmd^{-1}], $S_a(h)$ is the root water extraction rate [d^{-1}], and z is the vertical coordinate [cm] taken as positive upward.

A finite difference scheme is adapted in SWAP to solve the one-dimensional Richards equation with accurate and rapidly converging mass balance (van Dam *et al*., 1997). The relationship between soil hydraulic properties can be measured directly in the field or estimated from basic soil parameters such as soil texture using pedotransfer functions (PTFs) (Tietje and Hennings, 1996). In SWAP, these relationships are described by the well known analytical functions of van Genutchten (1980) and Mualem (1976) (Eqs. 4.2 and 4.3):

$$\theta(h) = \theta_{res} + \frac{\theta_{sat} - \theta_{res}}{\left[1 + |\alpha h|^n\right]^{\frac{n-1}{n}}} \quad (4.2)$$

$$K(\theta) = K_{sat} S_e^{\lambda} \left[1 - \left(1 - S_e^{n/n-1}\right)^{\frac{n-1}{n}}\right]^2 \quad (4.3)$$

Where: θ_{res} is the residual water content [cm^3cm^{-3}], θ_{sat} is the saturated water content [cm^3cm^{-3}], $S_e = (\theta - \theta_{res}) / (\theta_{sat} - \theta_{res})$ is the relative saturation [-], α is the empirical shape factor [cm^{-1}], n is empirical shape factor [-], K_{sat} is the saturated hydraulic conductivity [cmd^{-1}], and λ is an empirical coefficient [-].

Top boundary conditions

The potential evapotranspiration (ET_p), which together with precipitation (P-mm) and irrigation (I-mm) determine top boundary condition in SWAP, is estimated using the FAO Penman-Monteith equation (4.4) (Allen et al., 1998):

$$ET_p = \frac{\Delta \frac{(R_n - G)}{\lambda_w} + \rho_a c_p \frac{(e_s - e_a)}{\lambda_w}}{\Delta + \gamma_a \left(1 + \frac{r_c}{r_a}\right)} \quad (4.4)$$

Where: ET_p is potential evapotransipiration [mmd^{-1}], R_n is the net radiation [$MJm^{-2}d^{-1}$], G is soil heat flux [$MJm^{-2}d^{-1}$], (e_s-e_a) represents the vapor pressure deficit of the air [kPa], ρ_a is the mean air density at constant pressure [kgm^{-3}], c_p is the specific heat of the air [$MJkg^{-1}$ $°C^{-1}$], Δ represents the slope of the saturation vapor pressure-temperature relationship [$kPa°C^{-1}$], λ_w is the latent heat of vaporization [$MJkg^{-1}$], γ_a = psychrometric constant [$kPa°C^{-1}$], r_c is crop resistance [sm^{-1}], and r_a is aerodynamic resistance [sm^{-1}].

The daily estimate of ET_p using the FAO Penman-Monteith method, which is more relevant than monthly estimates in the context of the present study, requires daily weather observations of air temperature, solar radiation, air relative humidity and wind speed. Minimum crop resistance, crop reflectance and crop height are additional parameters needed to evaluate Eq. (4.4). SWAP partitions ET_p into potential transpiration rate (T_p) and potential soil evaporation rate (E_p), either using the leaf area index, LAI [m^2m^{-2}] (Eq. 4.5), or the soil cover fraction, SC [-], both as a function of crop development (Goudriaan, 1977; Belmans, 1983). The T_p and E_p refer to the rates at which transpiration and evaporation would occur in an ideal environment, defined as one with uniform vegetation cover, unlimited soil water supply and negligible advection or heat-storage effects. Reduction of T_p and E_p are then subsequently calculated according to physically based approach:

$$E_p = E_{po} e^{-\kappa_{gr} LAI} \tag{4.5}$$

Where: κ_{gr} [-] is the extinction coefficient for global solar radiation.

Under wet soil conditions, soil evaporation is determined by atmospheric demand (Allen et al., 1998) and equals potential soil evaporation rate (E_p). Under drier soil condition the maximum evaporation rate from the topsoil is calculated based on Darcy's law (Eq. 4.6):

$$E_{max} = K_{1/2}\left(\frac{h_{atm} - h_1 - z_1}{z_1}\right) \tag{4.6}$$

Where: $K_{1/2}$ is the average hydraulic conductivity [cmd^{-1}] between the soil surface and the first node, h_{atm} is the soil water pressure head [cm] in equilibrium with the air relative humidity, and Z_1 is the soil depth [cm] at the first node.

To limit overestimation of E_{max} due to physical disturbances on topsoils, SWAP uses the empirical evaporation functions of Black et al. (1969) or Boesten and Stroosnijder (1986) to limit soil evaporation rates. The evaporation function of Black et al. (1969) is utilized in this study.

SWAP calculates T_p (cmd^{-1}) (Eq. 4.7) taking into account the fraction of the day during which the intercepted water evaporates as well as the potential soil evaporation (E_p):

$$T_p = \left(1 - \frac{P_i}{ET_{wo}}\right) ET_{po} - E_p \quad with \qquad T_p \geq 0 \tag{4.7}$$

Where: P_i is the rainfall intercepted [mmd^{-1}] by the crop, and ET_{po} is the potential evapotranspiration [mmd^{-1}] of a wet crop, which can be estimated by the FAO Penman-Monteith (Eq. 4.4) assuming zero crop resistance. The ratio P_i/ET_{wo} denotes the day fraction, W_{frac}, during which intercepted water evaporates and transpiration is negligible.

Soil root extraction and actual plant transpiration

For a given plant rooting depth, the maximum root water extraction rate (S_p) is equal to the potential transpiration rate T_p (cmd^{-1}) governed by atmospheric conditions influenced by physical soil properties (Kroes and van Dam, 2003). In SWAP, a uniform root length density distribution is assumed (Eq. 4.8):

$$S_p(z) = \frac{T_p}{D_{root}} \tag{4.8}$$

Where: z is rooting depth [cm], and D_{root} is the root layer thickness [cm].

Drier or wetter soil conditions and/or high salinity concentration induce stress during crop growth. Water stress in SWAP is described by the relationship between critical soil water pressure head (h) and reduction factors for water (αrs) according to

Feddes et al. (1978) (Figure 4.2). In this study, irrigation water is assumed to be salt free, and crop plants were only affected by water stress.

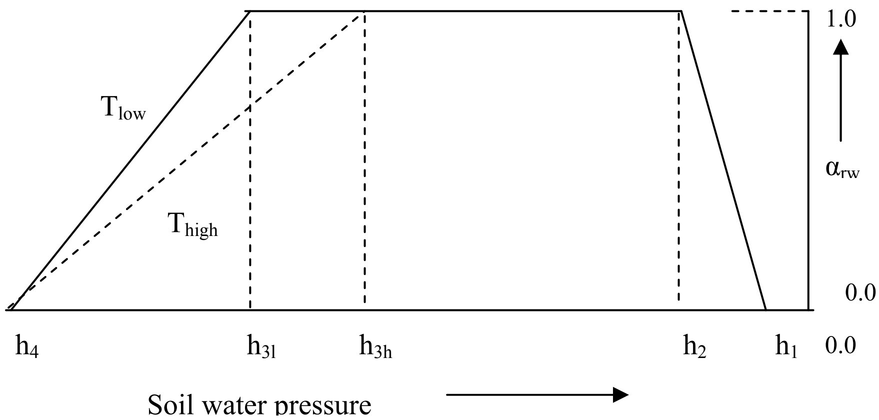

Figure 4.2: Reduction coefficient for root water uptake, α_{rs} as function of soil water pressure head h and potential transpiration rate T_p (after Feddes et al., 1978).

Bottom boundary and initial conditions

Soil water flux in SWAP is controlled by spatial differences of the soil water potential. Soil water potential is defined as the difference in potential energy per unit quantity of water between the soil water and the reference body of water (Jury et al., 1991). In SWAP, water flow is assumed to occur mainly in a vertical direction for the unsaturated zone of the soil profile, while in the saturated zone, water moves in three directions depending on pressure gradients (van Dam *et al.*, 1997). Three types of conditions are used to define bottom boundary conditions in SWAP. These are the Drichlet, Neuman and Cauchy conditions (Kroes and van Dam, 2003). With the Drichlet condition, the pressure head, *h,* is often specified as the recorded phreatic surface of the actual present groundwater table. The Neuman condition is applied when an impermeable layer can be identified or where deep groundwater exists resulting in free drainage. Under the Cauchy condition, unsaturated flow models are combined with regional groundwater flow. The Drichlet and Neuman conditions were applied in this study by prescribing the groundwater level and allowing free drainage where the groundwater level was at least 3 m below the soil surface.

Soil water balance analysis

The soil water balance of a vertical soil profile under field conditions can be stated as:

$$\Delta W = P + I - SD - T - E + Q_{bot} \tag{4.9}$$

Where: ΔW is the change in soil water storage [mm], P is the rainfall [mm], I is the irrigation [mm], SD is the surface drains [mm], T is the actual transpiration [mm], E is the actual soil evaporation [mm], and Q_{bot} is the water percolation [mm] at the bottom of the soil column (positive upward).

Water productivity estimation

Several indictors can be used for water productivity (WP) for a defined system in space and time. At field scale (plot), WP can be defined as a ratio of crop yield (total biomass or marketable yield) and cumulative amount of transpiration (T) or evapotranspiration (ET) or irrigation supply (I):

$$WP_T = \frac{Y[kg]}{T[m^3]} \tag{4.10}$$

$$WP_{ET} = \frac{Y[kg]}{ET[m^3]} \tag{4.11}$$

$$WP_I = \frac{Y[kg]}{I[m^3]} \tag{4.12}$$

Where: WP_T, WP_{ET} and WP_I are in kgm^{-3}. WP_{ETa} and WP_{ETc} will be used in the results and discussion sections to differentiate between WP estimations based on crop actual evapotranspiration simulated with SWAP and potential crop evapotranspiration estimated with the FAO-Penman Monteith method.

Plots sampling and description

Six farm plots, two at Tono and four in Dorongo, were identified for monitoring and collection of input data in the 2005/06 dry season for SWAP simulation. The plots were selected on a stratified random basis in the upper, center and lower part of the farm at Tono and Dorongo scheme. All of the plots except one in Dorongo were pre-wetted and plowed with a tractor or an oxen-drawn plow. The plots were planted with tomatoes (*Lycopersicon esculentum*). In Tono, the plots were planted on 19 and 9 December 2005, while planting in Dorongo was done on 15, 17 and 8 November 2005 for plot1, plot2 and plot3 and on 29 December 2005 for plot4. The length of tomato growth from planting to final harvest was 104 and 116 days in Tono, and 118, 120, 111 and 108 days in Dorongo. Both plots in Tono were irrigated with surface canal water. Three plots in Dorongo were irrigated with surface canal and one using pumped water from a small reservoir. The irrigation pumps in the study area are owned and controlled by the farmers. Plot areas varied from 0.34 to 0.35 ha in Tono and from 0.04 to 0.9 ha in Dorongo. The frequency of irrigation and harvested crop yield per plot were recorded during the farming season.

Determination of input parameters for SWAP

Meteorological parameters

Potential evapotranspiration (ET_p), rainfall and irrigation define the top boundary condition in SWAP. ET_p was estimated with (Eq.4.4) using daily meteorological data. In Tono, an automated HOBO weather station (Onset Computer Corporation) was installed in August 2005 to record the climatic parameters temperature, relative humidity, solar radiation, wind speed, and rainfall. The climatic variables were recorded from August 2005 to May 2006. For Dorongo, the climatic variables temperature, relative humidity, wind speed, sunshine hours, and rainfall for the period of January 2005 to April 2006 were obtained from Ghana Meteorological Services (GMS) for the Bolgatanga weather station.

Irrigation inflows

V-notch weir boxes (max. $12x10^{-3}m^3s^{-1}$) were fabricated and calibrated by repeatedly recording the time used to fill a container of known volume past the V-notch weir. The Weirs were installed in each plot to measure plot irrigation inflows. The water level above the crest of the weir and time of irrigation were recorded during each irrigation event, and the flow rate estimated using equation (Eq. 4.13) for V-notch weirs. Total volume of irrigation (V_T) per plot for the period of crop growth was obtained as a summation of the product of flow rate (Q) and time (t) of irrigation (Eq. 4.14):

$$Q = 0.071143h^{2.48} \tag{4.13}$$

$$V_T = \sum_{i,j=1}^{N}(Q_i t_j) \tag{4.14}$$

Where: Q is the flow rate [m^3s^{-1}], h is the head of water [m] above the crest of the V-notch, V_T is the total volume of irrigation for the duration of crop growth per plot [m^3], t is the time of irrigation for each irrigation event (s), and i and j represent the number [-] of irrigation events from the first to the last event (N).

Crop parameters

To specify a simple crop module, SWAP requires the following inputs: length of crop cycle (LCC) or temperature sum from crop emergence to anthesis, and from anthesis to crop maturity (TSUMEA & TSUMAM); light extinction coefficients for diffuse and direct visible light (KDIF & KDIR), leaf area index (LAI) or soil cover fractions (SCF), crop factors (kc) or crop height (CH), rooting depth (RD), yield response factors (K_y), critical pressure head (h) for crop root water uptake, canopy resistance (RSC), and levels of atmospheric demand (ADCRH & ADCRL). LCC was obtained from field observations, and TSUMEA and TSUMAM were estimated from average air temperatures recorded at the weather stations in the two sites during the respective crop development stages. SWAP default values of 0.60 and 0.75 for KDIF and KDIR were assumed and used in the simulation. LAI, CH and RD as functions of crop development were observed under field conditions. K_y values as functions of crop development stage were obtained from FAO records for tomato crop (Allen et al., 1998). h, RSC, ADCRH and ADCRL for tomato were obtained from Kroes and van Dam (2003). Table 4.1 shows selected crop parameters specified in SWAP.

Table 4.1: Selected crop parameters specified in SWAP crop input for water balance simulation

Plot	LCC (d)	TSUMEA (^{0}C)	TSUMAM (^{0}C)	Critical pressure heads (cm) h1	h2	h3l	h3h	h4	RSC (cm^{-1})	ADCRH (cmd^{-1})	ADCRL (cmd^{-1})
Tono											
Plot1	104	1245.28	1737.13	-1.0	-30.0	$-15x10^2$	$-8x10^2$	$-16x10^3$	50.0	1.0	0.2
Plot2	116	1304.03	2001.02								
Dorongo											
Plot1	118	1548.0	1873.0	-1.0	-30.0	$-15x10^2$	$-8x10^2$	$-16x10^3$	50.0	1.0	0.2
Plot2	120	1544.0	1914.8								
Plot3	111	1450.5	1726.3								
Plot4	108	1412.8	1691.0								

Soil sampling and laboratory analysis

At least one soil profile was excavated in each plot to depths ranging from 0.8 to 1.4 m below the soil surface. Disturbed (29) and undisturbed core (58) soil samples were collected for each horizon of the soil profile. The soil samples were transported to the Kumasi Soil Research Institute for analysis. Disturbed soil samples were analyzed for soil texture by the hydrometer method (Day, 1965), organic carbon and organic matter content by the wet oxidation method of Walkley and Black (Nelson and Sommers, 1996). Undisturbed soil samples were analyzed for volumetric saturated water content and bulk density (Black and Hartge, 1986). Laboratory analysis to determine field capacity (FC), permanent wilting point (PWP) and moisture retention characteristics for undisturbed core soil samples could not be done, because the required equipment (suction cell apparatus and pressure plate) were broken at the time the soil samples were transported to the laboratory. As an alternative, Pedotransfer functions (PTF) were utilized for analysis of soil hydraulic properties.

Soil hydraulic parameters

Initial parameters of the van Genuchten-Mualem analytical PTFs (Eq. 4.2 and 4.3), which are inputs to SWAP, were estimated with the Rosetta model (Schaap et al., 2005) using soil texture data. Initial estimates of θ_s by Rosetta were replaced with field-observed values. However, estimated K_{sat} values were retained for the input, since no observed values were available from the field, and estimates were within common ranges of K_{sat} for the soils studied. Since a value near to zero can be used for θ_r (Kool et al., 1987, van Genuchten, 1980), a constant value of 0.01 was applied for all soil profiles to allow a more flexible range on simulated soil moisture. Initial λ estimates were retained for input into SWAP. Soil hydraulic property simulations are generally sensitive to parameters α and n, and for reliable estimates, optimized values of these parameters are desirable.

Soil profile discretization

A 200-cm deep soil profile was specified for simulating the soil water balance. The soil profile was specified to a depth of about 140 cm and divided into soil horizons ranging from one up to four layers per soil profile. The soil column was further discretized into a total of 32 compartments with a nodal distance of 1 cm for the top 10 compartments, followed by 5 cm for the next 10 compartments and 10 cm for the remaining compartments. This scheme of soil profile discretization was important since for accurate simulation of dramatic changes in soil water content, the thickness of the top compartments should not be more than 1 cm (Kroes and van Dam 2003).

Parameter optimizations

Successful prediction of water transport using SWAP depends on reliable estimates of soil hydraulic conductivity and moisture contents. To minimize uncertainties in estimates of the soil water balance, the soil hydraulic conductivity and moisture content relationships were optimized with the non-linear parameter estimation program (PEST) (Doherthy et al., 1995) linked automatically to SWAP. The objective function Φ(b) was specified for the optimization process as (Eq. 4.15):

$$\Phi(b) = \sum_{i=1}^{N} \left[W_\theta (\theta_{obs}(t_i) - \theta_{sim}(b, t_i)) \right]^2 \tag{4.15}$$

Where: θ_{obs} (t_i) is the observed soil moisture at time t_i, N is the number of observations, θ_{sim} (b, t_i) is the simulated value of θ using an array with parameter values b, W_θ (=1) is the weight associated with θ_{obs}.

Daily values of θ_{obs} were measured with a soil moisture profiling probe (Delta-T Devices Ltd; Figure 4.3) for each plot at depths of 10 cm, 20 cm, 30 cm, 40 cm, 60 cm and 100 cm below the soil surface. Observed soil moisture profiles were used for calibration and validation of soil hydraulic parameters within SWAP using a simple crop module applied in the calibration and validation process.

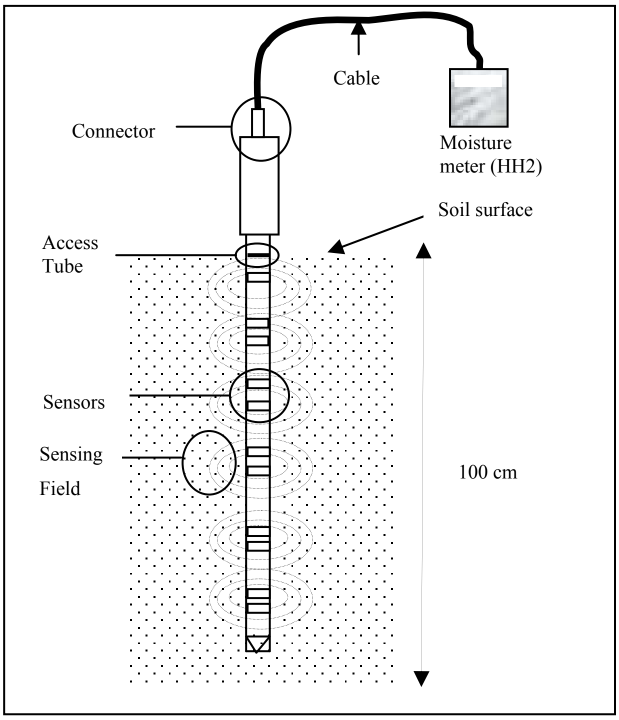

Figure 4.3: Layout of profile soil moisture measurement with the Profile Probe (PR2)

The Mean Error (ME) and the Root Mean Square Error (RMSE) between observed and simulated moisture content for each soil profile layer were used to assess the accuracy of the SWAP soil water balance simulation:

$$ME = \frac{1}{N}\sum_{i=1}^{N}(\theta_o - \theta_s) \tag{4.16}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\theta_o - \theta_s)^2} \tag{4.17}$$

Where: θ_o and θ_s are observed and simulated moisture content, and N is the number of observations over which *ME* and *RMSE* values were calculated.

Bottom boundary and initial conditions

Piezometric water levels from shallow piezometers installed in each of the monitored fields were utilized to define the bottom boundary condition for SWAP simulation.

Water levels in the piezometers were recorded at daily intervals. Water levels in open boreholes recorded at the beginning of the season or initial soil moisture generated by running SWAP for the previous rainy season (May-September/June-October) were used as model initial conditions.

4.3 Soil water balance and physical WP at farm and scheme level

Irrigation diversion: Tono farm and Dorongo scheme

Long Throated Flumes (LTFs) (Figure 4.4) were designed using WinFlume 1.05, a computer program for design and calibration of LTFs, and broad crested Weirs for open-channel water flow measurement (Wahl, 2001). The LTFs were installed on the two laterals of Zone-M farm in Tono, and on two diversion canals in the Dorongo scheme. Discharge equations (Eqs. 4.18-4.21) fitted to WinFlume's hydraulic theory and discharge curves were generated and calibrated. Stilling wells were fabricated and installed in each LTF.

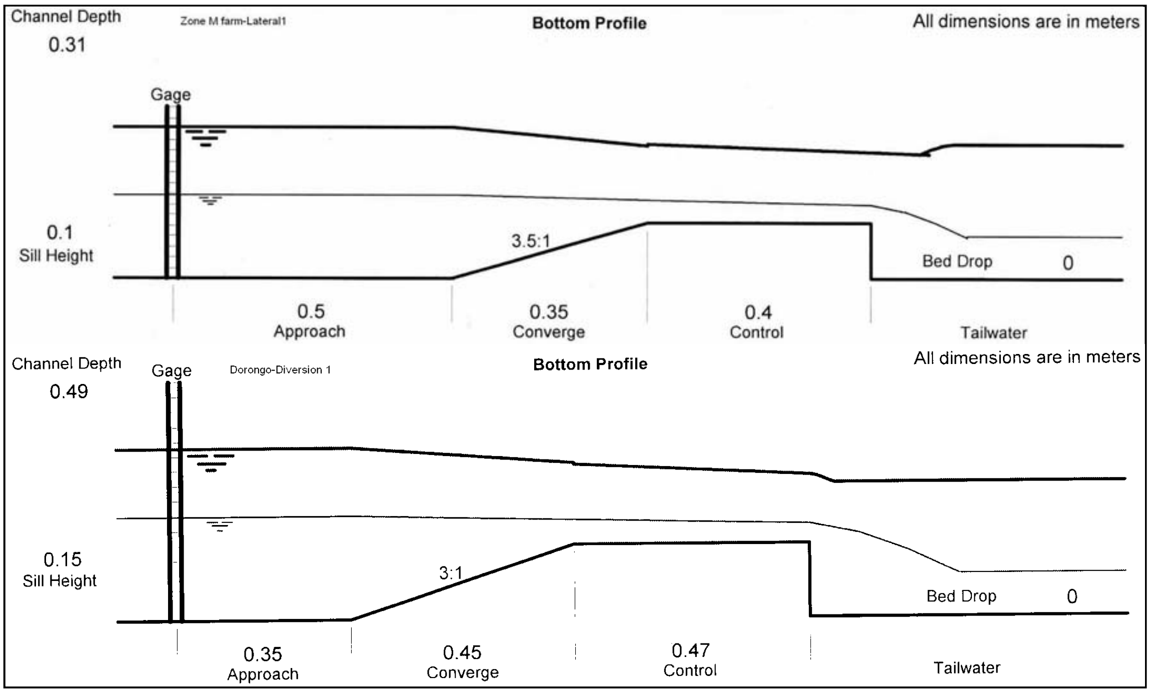

Figure 4.4: Sketch of LTFs for the first laterals of Zone-M farm in Tono and Dorongo scheme

Automatic water level recorders (divers) were installed in the LTF stilling wells for recording water levels during irrigation events. Irrigation flow rates in the laterals and diversion canals were estimated with LTF-generated discharge equations using recorded water levels. The total volume of water diverted for the irrigation season was estimated (Eq. 4.14):

$$Q_{M1} = 1.220(h + 0.0159)^{2.123} \tag{4.18}$$

$$Q_{M2} = 1.561(h + 0.0264)^{2.196} \tag{4.19}$$

$$Q_{D1} = 1.368(h + 0.0126)^{2.042} \tag{4.20}$$

$$Q_{D2} = 1.269(h + 0.0821)^{2.042} \tag{4.21}$$

Where: Q_{M1}, Q_{M2}, Q_{D1}, Q_{D2} are flow rates [m^3s^{-1}] for the two laterals in Zone-M farm at Tono and the two diversion canals in Dorongo

Irrigation diversion: Tono scheme

Water level records for the main canal covering the period between January 2005 and April 2006 were collected from the Tono project farm. The water levels were applied to the existing Parshall flume's flow rate equation (Eq. 4.22) to estimate canal water flows for the 2005/06 dry season. The Parshall flume's flow rate equation was calibrated on the basis of current-meter measurements (Type A.OTT, No 46623; Propeller No 1-47395, diameter 125 mm) made on the Parshall flume discharge.

$$Q = 4.39h^{1.53} \tag{4.22}$$

Where: Q is the flow rate [m^3s^{-1}] and *h* is the water level (m) recorded in the stilling well of the Parshall flume. Total volume (V_T) of water flowing (m^3) during the study period (Oct 2005-May 2006) was estimated with Eq. (4.14).

Crop water use

The FAO-Penman Monteith (Eq. 4.23) (Allen et al., 1998) was utilized to estimate the reference evapotranspiration using climatic data collected from the Tono and Bolgatanga weather stations:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{4.23}$$

Where: ET_0 is the reference (potential) evapotranspiration [mmd^{-1}], R_n is the net radiation [$MJm^{-2}d^{-1}$], G is the soil heat flux density [$MJm^{-2}d^{-1}$] assumed equal to 0 for daily interval calculation of ET_o, T is the average daily temperature [°C], U_2 is the wind speed at 2 m height [ms^{-1}], e_s is the saturation vapour pressure [kPa], e_a is the actual vapor pressure [kPa], e_s-e_a is the saturation vapor pressure deficit [kPa], Δ is the slope of the vapour pressure curve [kPa°C^{-1}], and γ is the psychrometric constant [kPa°C^{-1}].

Crop factors (k_c) for tomatoes, rice, soybean onions, maize, pepper and other leaf vegetables were obtained from FAO guidelines for crop water requirements (Allen et al., 1998) and adjusted based on local crop growth conditions and water supply. Crop potential evapotranspiration was estimated using equation (4.24):

$$ET_c = k_c ET_o \tag{4.24}$$

Where: ET_c is the crop potential evapotranspiration [mmd^{-1}], and k_c is crop factors [-]

Cropped areas during the growing season were estimated with ARCVIEW GIS 3.2 from GPS surveys on the cropped plots, and by physical measurements at Zone-M farm in Tono and at the Dorongo scheme. Crop water demand for the entire cropped area was then estimated (Eq. 4.25):

$$CWD = \sum_{i=1}^{N} (ETc_i \times A_i) \qquad (4.25)$$

Where: *CWD* is the crop water demand [m^3], A is the area [ha] planted for each crop, and *i* to *N* represent the number of crop season days for the planted crops.

Surface drainage flows

Zone-M farm at Tono

Cross sections of three drainage channels (Figure 4.5) were surveyed with an automatic level to establish the lowest surface elevation in the drainage channel. Two V-notch weirs (0.07 m^3s^{-1}) were installed to measure drainage on the right and left banks of the farm, 50 m above the point where the drains join the main farm drain. Water level staff gages were installed at the lowest point in the channel on the two V-notch Weirs, and immediately at the exit of the main drain from Zone-M farm, to account for surface and sub-surface drains adjoining the main drain directly from the farm. Current-meter flow measurements (Type A.OTT, No 46623; Propeller No 1-47395, diameter 125 mm) were carried out at different flow volumes at the exit point of a main drain, and the rating curve equation (4.26) was established:

$$Q = 0.1958h^{1.2143} \qquad (4.26)$$

Where: *Q* is the flow rate [m^3s^{-1}], and h is the water level [m].

Water levels were recorded at staff gauges twice a day (0900 and 1700 hrs). The two measurements were averaged to obtain average daily water levels. These values were inserted in the flow rate equation for V-notch weirs (Eq. 4.13) and (Eq. 4.26) to calculate the daily flow rates at the farm main drain. The total volume of drainage flow in each drainage channel over the study period was estimated (Eq. 4.14), and the volume of drainage for the entire farm was obtained by a summation of the three drain volumes.

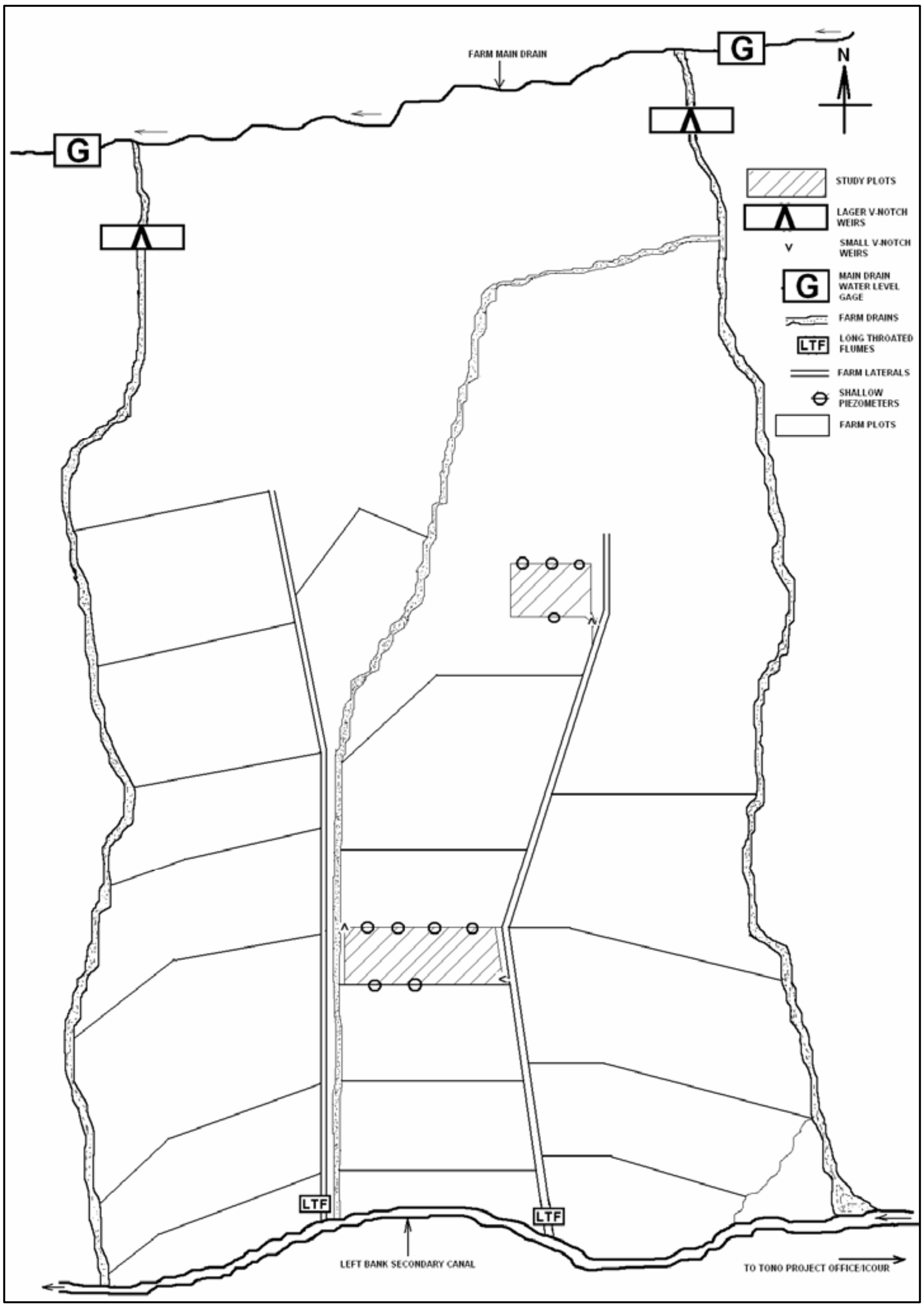

Figure 4.5: Layout of Zone-M farm at Tono (Not drawn to scale)

Dorongo scheme

A bucket-stopwatch approach (suitable for low flow volumes) was applied to measure drainage outflows in Dorongo. The drain water was impounded by blockade and a 7.62 cm PVC pipe was installed at the drain outlet. The drainage was measured twice a day (0900 and 1800 hrs) from October to December 2005. The time to fill the bucket with a known volume was recorded, and the flow rate (Q-m^3s^{-1}) calculated as the ratio of bucket volume (m^3) to the time (sec) used to fill the bucket. Daily average flow rate was estimated from the two daily measurements. Total volume drained for the study period was calculated (Eq. 4.14).

Tono scheme

The cross section of Tono River at the exit from the scheme was surveyed with an automatic level, and the lowest point on the channel was established (Figure 4.6). A water level gage was installed at the lowest point. Flow rate measurements were carried out at different water levels regularly with a current meter (Type A.OTT, No 46623; Propeller No 1-47395, diameter 125 mm). The rating curve (Fig. 4.5) and rating equation (Eq.4.27) were generated using flow rate and water level measurements.

$$Q = 0.257h^{3.5725} \tag{4.27}$$

Where: Q is the flow rate (m^3s^{-1}) and h is the water level (m).

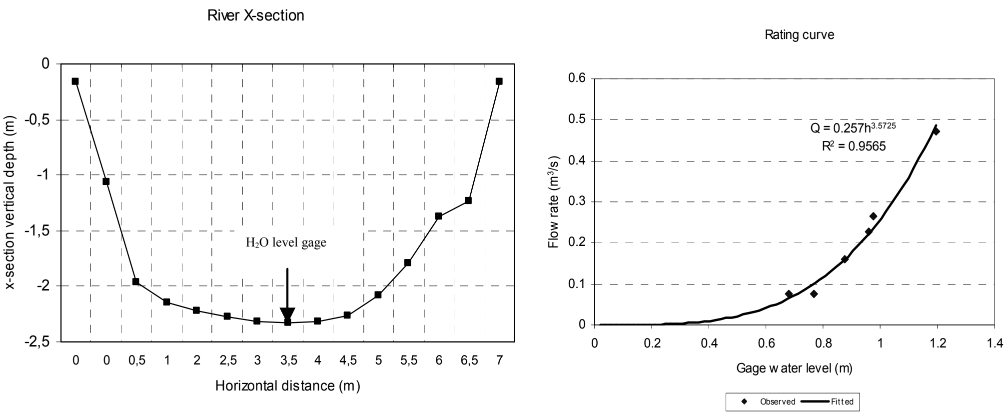

Figure 4.6: Tono River cross section and rating curve at drainage measurement point

Water levels were recorded manually twice daily (0900 and 1700 hrs) from November 2005 to May 2006. The average daily water level was obtained, and the daily flow rate calculated using the rating equation. The total volume of water drained for the study period was determined (Eq. 4.14).

Percolation and evaporation losses

Deep groundwater percolation and non-beneficial evaporation losses were estimated as residuals in the water balance equation (Eq. 4.28), assuming the seasonal soil moisture storage change is negligible because of minimal differences in soil moisture between the beginning and at the end of the crop season:

$$(Q_{bot} + E_{nb}) = ET_c + SD - P - I \tag{4.28}$$

Where: $Q_{bot}+E_{nb}$ is the groundwater percolation and non-beneficial evaporation [mm].

Non-beneficial evaporation was assumed to occur mainly by vegetation evapotranspiration from fallow plots and undeveloped areas within the farm or scheme.

Water productivity estimation

For Tono, average long-term crop yields and average seasonal crop water requirements (Eq. 4.25) were utilized to estimate WP at farm and scheme levels, since there were no irrigation measurements per individual crop. The average long-term crop yields were estimated using yield records obtained from the Tono farm project office. At Dorongo, average seasonal crop yield was estimated from sample monitored plots. The WP was determined in terms of irrigation supply (WP_I) and average crop potential water requirements (WP_{ETc}).

4.4 Results and discussion

4.4.1 Climatic variables (top boundary conditions)

The average daily values of temperature, relative humidity, solar radiation, and wind speed at Tono and Bolgatanga weather stations during the 2005/06 dry season were determined (Figure 4.7).

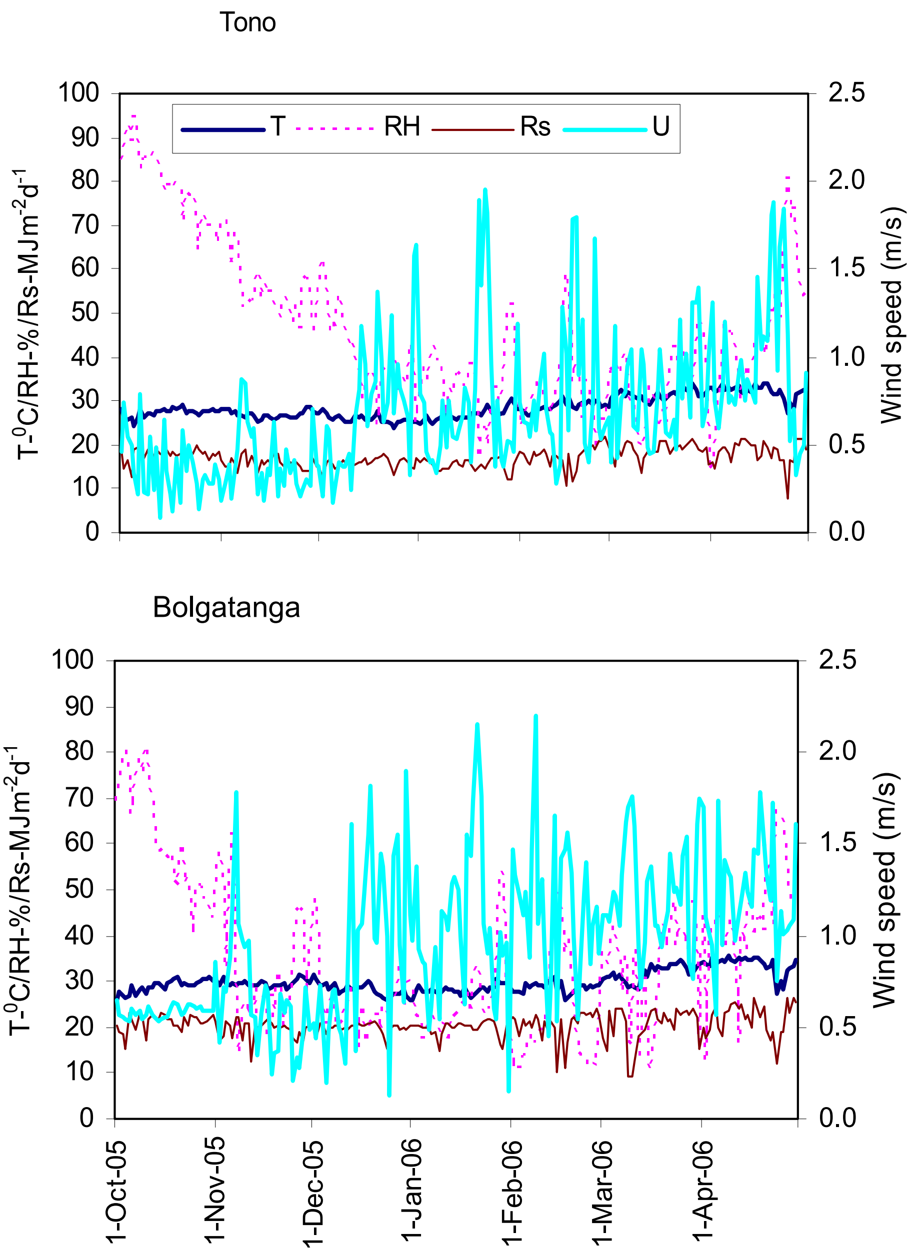

Figure 4.7: Daily temperature (T), relative humidity (RH), solar radiation (Rs) and wind speed (U) at Tono and Bolgatanga during 2005/06 dry season

At Tono, temperature varied from 24°C to 34°C (mean 29°C). Relative humidity ranged between 14% and 95% (mean 47%); the highest values were recorded in October and the lowest in March. Solar radiation ranged between 8 and 22 $MJm^{-2}d^{-1}$ (mean 17 $MJm^{-2}d^{-1}$), and wind speed varied from 0.09 to 2.17 m/s (mean 0.74 m/s). At Bolgatanga, the average daily temperature varied from 26°C to 36°C (mean 30°C).

Relative humidity ranged from 11-82% (mean 35%). Solar radiation varied from 9 to 26 $MJm^{-2}d^{-1}$ (mean 20 $MJm^{-2}d^{-1}$). Wind speed varied from 0.13 to 2.20 m/s (mean 0.97m/s). The systematic differences between Tono and Bolgatanga, i.e., lower temperature, higher relative humidity at Tono, are likely due to the proximity of the Tono station to a sizeable water body.

4.4.2 Soil hydraulic parameter optimization

Soil types and soil hydraulic parameters for the van Genuchten-Mualem analytical PTFs were determined (Table 4.2). The parameters α and n were optimized using PEST. At Zone-M farm in Tono, the soils consisted mainly of sandy loam in the top- and sub-soils and a layer of silt in the profile of plot1. Saturated soil water content (θ_s) was about 0.40 cm^3cm^{-3} and saturated soil hydraulic conductivity (K_{sat}) was moderate (81.94 cmd^{-1}) for sandy loam and slow (42.58 cmd^{-1}) for silt. In Dorongo, the topsoils were mainly loam, sandy loam and silt loam with sub-soils varying from sandy loam to clay loam. Saturated water content was 0.39 cm^3cm^{-3} for sandy loam and 0.42 cm^3cm^{-3} for silt loam. Saturated water content ranged from 0.38 to 0.41 cm^3cm^{-3} for loam, 0.44 to 0.49 cm^3cm^{-3} for sandy clay loam and 0.53 cm^3cm^{-3} for silt clay loam. Saturated water content varied from 0.44 to 0.54 cm^3cm^{-3} for clay loam and 0.52 cm^3cm^{-3} for sandy clay. K_s ranged from slow (19-48 cmd^{-1}) to moderate (48-144 cmd^{-1}) for sandy loam. K_s was slow for silt loam and very slow (<19 cmd^{-1}) for loam, sandy clay loam, silt clay loam, clay loam and sandy clay soils.

Table 4.2: Soil texture and analytical PTFs soil hydraulic parameters

Plot No.	Soil layer (cm)	Texture	Soil hydraulic parameters					
			θ_r (cm^3cm^{-3})	θ_s (cm^3cm^{-3})	α (cm^{-1})	n (-)	K_s (cmd^{-1})	λ (-)
				Tono				
1	0-20	SL	0.01	0.32	0.020	1.95	81.94	0.97
	20-40	Si	0.01	0.32	0.010	2.64	42.58	0.87
	40-200	SL	0.01	0.35	0.010	3.00	81.94	0.97
2	0-200	SL	0.01	0.34	0.010	2.50	85.00	0.97
				Dorongo				
1	0-20	L	0.01	0.41	0.010	1.90	14.32	-0.36
	20-40	CL	0.01	0.44	0.012	1.94	12.50	-0.82
	40-80	SCL	0.01	0.44	0.026	1.49	12.77	-0.86
	80-200	SCL	0.01	0.49	0.018	1.27	17.75	-0.81
2	0-20	L	0.01	0.38	0.010	2.40	27.30	-0.23
	20-40	SL	0.01	0.39	0.030	1.56	30.75	-0.72
	40-80	L	0.01	0.41	0.010	1.37	12.36	-0.53
	80-200	CL	0.01	0.49	0.010	1.32	11.02	-0.79

Table 4.2 continued…

3	0-20	SL	0.01	0.39	0.050	3.00	71.15	-0.96
	20-40	SL	0.01	0.39	0.080	1.10	42.83	-0.90
	40-80	SC	0.01	0.52	0.010	1.10	18.42	-1.86
	80-200	CL	0.01	0.54	0.010	1.10	9.42	-0.72
4	0-20	SiL	0.01	0.42	0.006	3.00	21.01	0.22
	20-40	CL	0.01	0.44	0.005	1.10	9.63	-0.62
	40-90	CL	0.01	0.54	0.005	2.99	7.21	-0.17
	80-200	SiCL	0.01	0.53	0.007	1.17	12.01	-0.09

Where: SL sandy loam, Si silt, L loam, CL clay loam, SCL sandy clay loam, SC sandy clay, SiL silty loam and SiCL silty clay loam

The parameters α and n were successfully optimized as indicated by relatively small mean errors (ME) (Table 4.3) and root mean squared errors (RMSE) (Table 4.4) between observed and simulated soil water contents for the different layers of the soil profile (Figure 4.9, plot2 at Dorongo).

Table 4.3: ME between observed and simulated soil moisture content (cm^3cm^{-3})

Profile depth (cm)	Tono		Dorongo			
	Plot1	Plot2	Plot1	Plot2	Plot3	Plot4
0-20	-0.002	-0.019	-0.001	-0.006	-0.012	-0.042
20-30	-0.037	-0.021	-0.001	0.015	-0.037	-0.014
30-40	0.010	-0.006	-0.001	-0.016	-0.036	0.003
40-60	-0.002	-0.004	-0.029	0.001	0.019	-0.020
60-100	0.019	0.009	0.037	0.004	0.021	-0.012

Table 4.4: RMSE between observed and simulated soil moisture content (cm^3cm^{-3})

Profile depth (cm)	Tono		Dorongo			
	Plot1	Plot2	Plot1	Plot2	Plot3	Plot4
0-20	0.034	0.035	0.025	0.02	0.028	0.068
20-30	0.042	0.030	0.021	0.02	0.087	0.027
30-40	0.027	0.019	0.017	0.02	0.040	0.033
40-60	0.018	0.019	0.063	0.01	0.032	0.039
60-100	0.027	0.013	0.047	0.01	0.029	0.017

The analysis results show that predicted soil moisture for the topsoils is relatively more variable than that of the sub-soils (Figure 4.8). The discretization of soil layers to a thickness of 1 cm in the topsoil profile makes it possible for SWAP to simulate small changes in soil moisture with high accuracy. However, the general trend in simulated soil moisture content is not different from that of measured soil moisture content. Although the ME do not indicate systematic under-/or over-estimation relative to measured soil moisture levels, differences between observed and simulated soil water contents could result from installation and/or sampling errors (0.006 or 0.6%-Delta-T Devices) in the measurement of moisture contents and K_{sat}.

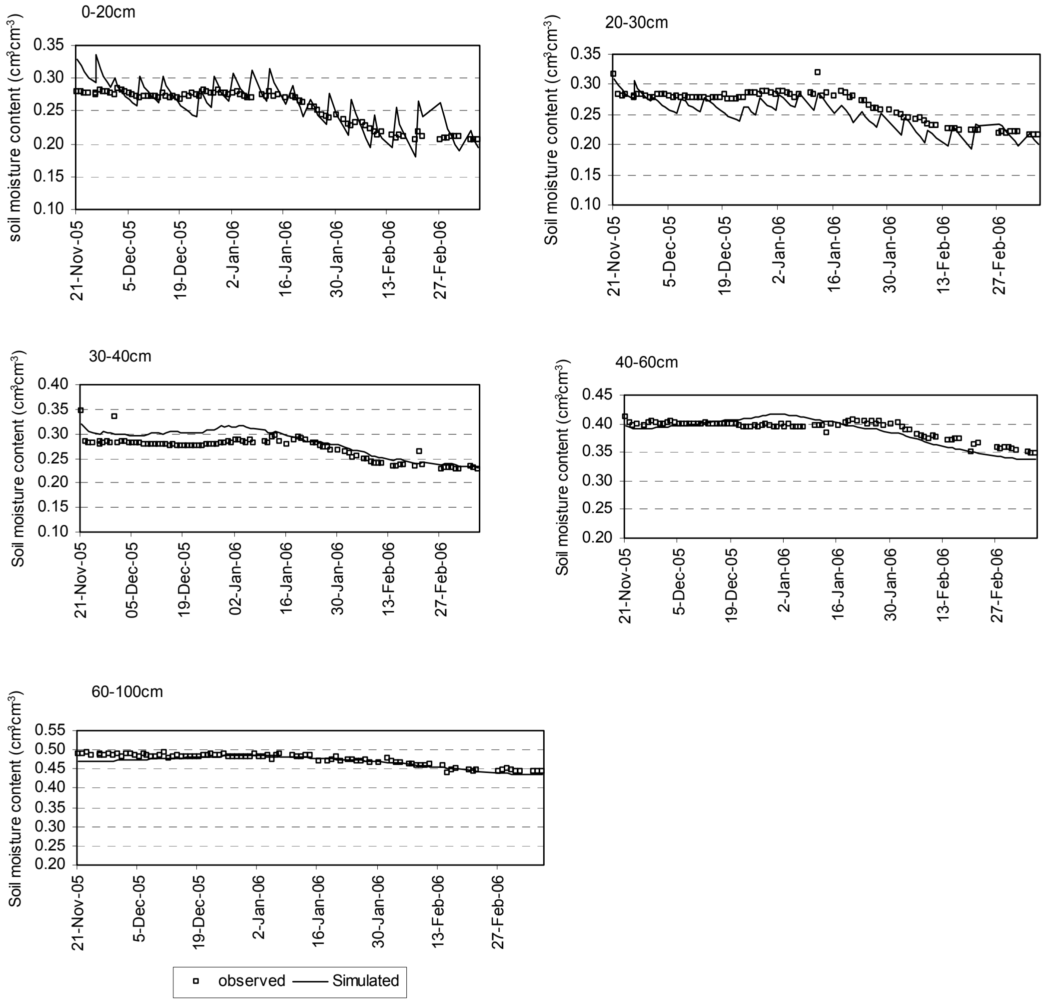

Figure 4.8: Observed and simulated soil moisture profiles at plot2 in Dorongo during 2005/06 dry season

4.4.3 Soil water balance

Field (plot) level

Soil water balances were simulated using SWAP at field level at Tono and Dorongo (Table 4.5). Precipitation (P) varied from 9.8 to 12.6 mm between the two sites. Average irrigation per plot at Tono was 788 mm, while at Dorongo average irrigation was 530 mm. The amount of irrigation water was larger than SWAP-simulated ET_a by 40% to 70% in Tono. At Dorongo, irrigation water was lower than ET_a by 23% for plot1. In the remaining plots, irrigation was higher than simulated ET_a by 15%, 11% and

40% for plots 2, 3 and 4, respectively. Plot4 in Dorongo had the highest irrigation (668 mm). Due to the large amount of irrigation water, groundwater percolation (Q_{bot}) was higher at Tono than at Dorongo. The average Q_{bot} was -340.7mm at Tono and 38.8 mm at Dorongo. At Dorongo, simulated Q_{bot} was highest in plot2 (-188.3 mm), and in plots 3 and 4, Q_{bot} values were lower (-6, 3 and -38.5 mm). In spite of high irrigation applications on plot4, a small Q_{bot} was measured, as almost 35% of the irrigation water appeared as surface drainage (SD), mainly during land preparation (soaking or pre-wetting). Although a lower amount of irrigation water was recorded in plot3 than in plot4, plot3 produced a high Q_{bot} value. A root zone capillary soil moisture contribution (77.9 mm) was only observed in plot1. The plot was located upstream of the scheme bordering the dam of the reservoir. The soil moisture contribution through capillary rise could be a result of leakage and seepage of reservoir water and not the typical root zone soil moisture stored from the previous season. With the exception of plot3 in Dorongo, SWAP simulations of the other plots at both sites indicate a decreased storage of profile soil moisture (ΔW) over the crop season. That could be attributed to the soil hydraulic system being in equilibrium with the groundwater level, and therefore percolation losses moved away from the plot boundaries in the direction of the groundwater flow.

Table 4.5: SWAP-simulated field soil water balances between November 2005 and April 2006 at Tono and Dorongo schemes

Soil water balance components	Soil water balance (mm)					
	Tono		Dorongo			
	Plot1	Plot2	Plot1	Plot2	Plot3	Plot4
P	9.8	9.8	12.6	12.6	12.6	12.6
I	852.0	724.0	380.0	581.0	488.0	668.0
Q_{bot}	-401.3	-280.0	77.9	-188.3	-6.3	-38.5
T	390.6	432.0	365.8	337.8	318.7	341.9
E	89.8	69.1	127.0	155.4	118.3	134.7
ET_a	480.4	501.1	492.8	493.2	436.0	476.6
SD	0.0	0.0	0.0	0.0	0.0	211.8
ΔW	-19.9	-47.3	-22.3	-87.9	57.3	-46.3
ET_c	492.0	545.0	503.7	526.9	434.2	466.1

Crop evapotranspiration may vary widely depending on environmental conditions, water supply, crop parameters and crop growth period. Long-term average annual ET_o at the Navrongo Weather Station is about 1936.2 mm (Kranjac-Berisavljevic et al., 1998). For the dry season (October-April), the long-term seasonal

ET_o is about 1143.6 mm. Assuming a pan coefficient (Class A Pan) of about 0.7 under light wind speed (<2 m/s) and low relative humidity (< 40%) (Allen et al., 1998), ET_c between November-March in the UER may range from 400 to 550 mm depending on length of crop growth, water supply and crop parameters.

Hanson and May (2006) estimated average ET_c of 648 mm for furrow-and drip-irrigated tomatoes grown during the summer in San Joaquin Valley California, USA. In Turkey, ET_c for furrow-and drip-irrigated tomatoes grown during the summer under the Mediterranean climate was about 700 mm during a 4-month growth period (Kocaman et al., 2002; Cetin et al., 2002). In South Africa, estimates of ET_c for 83 days varied from 321 to 342 mm (Javanovic and Annandale, 1999). Agele et al. (2002) obtained an ET_c value of 328.6 mm for a 4-month growth period toward the end of rainy season (September-January) in semi-humid south Nigeria. In southern highland semi-arid areas of Tanzania, ET_c ranged from 460 to 570 mm for dry season furrow-irrigated tomatoes (FAO, 2003). Laquet et al. (2004) estimated an annual maximum ET_c of 1200 mm for furrow-irrigated tomatoes in semi-arid areas. The annual ET_c was approximately equivalent to ET_c of 400 mm for a 3-month growth period.

In the UER, early tomato transplanting is done towards the end of October or beginning of November (on average), while late transplanting takes place until the end of December or beginning of January. Generally, crop growth is 3 months, but availability of water supply to late stage crop development may prolong crop growth up to 4 months. Favorable growth conditions for tomatoes are between October and February when the atmospheric demands for crop water use are not so high. From February onwards, temperatures increase rapidly reaching peak values in March and April. During this period, crop water demands are high. Therefore, an ET_c between 400 mm and 460 mm represents a lower boundary for a 3-month crop between October-January, while values of up to 570 mm may represent upper ranges for tomatoes harvested from March and beyond. Estimated ET_c values in all plots were within the reported ranges for tomatoes grown in semi-arid tropics. However, higher estimates of tomato ET_c in semi-arid tropics comparable to those of the summer season in temperate climates have been reported. For example, Yohannes and Tadesse (1998) estimated an ET_c of 670 mm for a 4-month tomato under furrow and drip irrigation in semi-arid Ethiopia. They calculated ET_c based on an ET_o estimated using the Banley Criddle method. Their study area was located over 1000 m above sea level, and high estimated ET_c might have been influenced by climatic conditions such as high wind speed and high vapour pressure deficit.

ET_a was close to ET_c in almost all the plots. At Tono, ET_c was higher than ET_a by 2 and 9% while at Dorongo, ET_c was higher than ET_a by 2 and 7% for plots 1 and 2, respectively. For plot3, ET_a and ET_c were almost the same, while ET_a for plot4 was higher than ET_c by 2%. The closeness agreement between ET_a and ET_c generally shows that crop plants were not seriously affected with water stress.

Farm level

Since the Dorongo scheme layout could not be separated into farms, analysis of soil water balance at farm level was done only for Tono (Table 4.6). About 25 ha out of 48 ha of Zone-M farm (ZMF) was cultivated and cropped with tomatoes (4 ha), soybean (3 ha), maize (1 ha) and rice (17 ha) in the 2005/06 dry season. Timing of transplanting and sowing of crops ranged from beginning of December to the end of January for tomatoes, end of January for soybean and maize, and from beginning to end of February for rice.

Effective precipitation (P) from December, at the start of farming activities in ZMF, to mid May was 100 mm. A gross amount of irrigation water of 1537 mm was supplied to the farm. Of the irrigation supply, 41% (626 mm) flowed out as surface drains (*SD*). The average ET_c for planted crops on the farm was 577 mm. Percolation and non-beneficial evaporation ($Q_{bot} + E_{nb}$ at farm level) accounted for 28% (434 mm) of the irrigation supply. For individual crops, average ET_c was 504 mm for tomatoes, 411 mm for soybean, 505 mm for maize and 630 mm for rice. Estimates of ET_c for rice included a period beyond 15 May when most of the rice fields were expected to have reached maturity.

Table 4.6: Soil water balance at farm level and ET_c for crops grown on Zone-M farm at Tono

Soil water balance components	Soil water balance (mm)	Crop	Estimated ET_c (mm)
P	100	Tomatoes	504
I	1537	Soy bean	411
ET_c	577	Maize	505
SD	626	Rice	630
$Q_{bot} + E_{nb}$	-434		

Generally, irrigation supply (including precipitation) was 3-times higher than the average ET_c, and more than 60% appeared as losses at farm level through surface drainage, percolation to groundwater and non-beneficial evaporation from non-cropped fields. Although *SD* and Q_{bot} are considered losses at farm level, they may not be true losses at scheme level if recovered and reused downstream within or below the scheme. However, since farm drains flows to the main course of Tono River, reuse entails additional costs of pumping water out from the river channel. Due to pumping costs, only few farmers use pump irrigation along the river channel, mainly for tomatoes farming.

Scheme level

Soil water balance at scheme level was determined for Tono and Dorongo (Table 4.7). About 800 ha were cultivated in Tono and planted with tomatoes (130.67 ha), rice (591.25 ha), Soybean (27.51 ha), maize (1.68 ha), cowpea (3.06 ha), pepper (4.95 ha), onions (27.48 ha) and other leaf vegetables (13.63 ha) during the 2005/06 dry season. Crop planting dates varied from October to December for most crops, and from the end of December to the beginning of March for rice. At Dorongo 9.8 ha were cultivated and planted mainly with tomatoes. Transplanting in Dorongo was concentrated between November and December.

Table 4.7: Soil water balance at scheme level for Tono and Dorongo and ET_c for different crops

Soil water balance components	Soil water balance (mm)	
	Tono	Dorongo
P	100.0	12.6
I	3313.3	430.1
ET_c	563.6	468.4
SD	484.0	29.6
$Q_{bot}+E_{nb}$	-2365.3	55.5
Estimated ET_c for crops		
Tomatoes	503.3	468.4
Rice	643.0	
Soybean	387.4	
Maize	483.4	
Cowpea	345.4	
Pepper	520.5	
Onions	455.7	
Other vegetables	493.8	

Precipitation accounted for about 100 mm at Tono and 12.6 mm at Dorongo. At Tono, irrigation supply was 3313.3 mm. Of the irrigation supply, 15% (484.0 mm) flowed outside the scheme as surface drains (SD). Average ET_c was 563.6 mm, and 2365.3 mm (71%) of the irrigation supply was consumed by non-crop vegetation, deep percolation losses and open surface water evaporation. At Dorongo, irrigation was 430.0 mm of which 7% (29.6 mm) flowed out as surface drainage. Average ET_c was 468.4 mm being higher by 56 mm than the net water supply (P+I) of 413 mm. Average ET_c for individual crops at Tono was 503.27 mm for tomatoes, 643.0 mm for rice, 387.4 mm for soybean, 483.4 mm for maize, 345.4 mm for cowpea, 520.5 mm for pepper, 455.7 mm for onions, and 493.8 mm for other vegetables. Higher ET_c for soybean and maize at farm level as compared to scheme level was due to a shift in planting periods. The crops were planted late during the season (19-23 January 2006) on the farm, while at scheme level the crops were mainly planted during December 2005.

The water balance component $(Q_{\text{bot}} + E_{nb})$ include the amount of water used for land preparation and flooding of rice plots, which can be up to about 300 mm (Guerra et al., 1998, Bhuiyan et al., 1995). Compaore (2006) obtained 3.45 and 1.45 mm/day for ET_a of vegetated surfaces in Tono at the start and end of the 2002/03 dry season, respectively. In the present study, using the average value of 2.45 mm/day, water use for the vegetated un-cropped area (1700 ha) between 1 October 2005 and 15 May 2006 was estimated at 679 mm. The non-cropped area consisted of 136 ha of mango and cashew nut trees (ICOUR, 2000), while the remaining 1564 ha were assumed to be under fallow and mixed vegetation, both actively transpiring water supplied through deteriorated canals and seepage and percolation occurring from the canals and irrigated fields. Assuming negligible domestic and animal consumption from irrigation canal water, deep percolation losses were estimated at 1386 mm, which was about 42% of the irrigation supply. Taking into account the effective rainfall during the crop season, irrigation water use efficiency at scheme level for Tono was only about 16%. At Dorongo, water use efficiency about 100% at scheme level.

Actual water requirement (ET_a) depends on climatic, water supply and crop growth conditions among other factors (Table 4.7). Rice is one of the cereals with a high crop water demand. Flooding, a common practice for rice farming in many rice-growing areas, increases demands for water in addition to ET_a. Rice may require over

1500 mm in tropics and sub-tropics (Guerra et al., 1998) because of the flooding practices employed in rice farming. In many rice farming areas, rice fields are flooded during land preparation to facilitate plowing and puddling the fields. Puddling reduces the permeability of the plow layer, significantly reducing deep percolation losses during subsequent continuous flooding after rice transplanting. Increased depth of flooded water in rice fields may, however, contribute to increased percolation losses. Other functional roles of flooding in rice fields include weed suppression resulting in reduction of herbicides application, associated costs and environmental consequences, and atmospheric cooling that reduces heat stress to crop plants. Flooding also is applied to avoid crop failure due to unexpected delays in water supplies. Incorporating these functional roles of flooding, which do not necessarily contribute to crop evapotranspiration, certainly may complicate WP assessment. Increased demands for water for rice production are therefore inherent to the farming practices. For example, in Morocco, paddy rice water use during summer varied from 1700 to 2500 mm (Lage et al., 2003). However, rice ET_a may vary from about 50% and more of the total rice water requirement. Soybean and pepper also shows a high crop ET_c (Table 4.8).

Table 4.8: Estimates of ET_c for various crops under different climatic conditions

ET_c [mm]	Source	Location
Rice		
450-700	FAO (1986)	General
665	Lage et al. (2003)	Morocco
586-599	Mohan et al. (1996)	Sub-humid south India
640	Jehangir et al. (2004)	Sub-tropical semi arid rice-wheat zone, Pakistan
Up to 800	Ahmad et al. (2004); Singh (2005)	Semi-arid climate (Pakistan and India)
Maize		
500-800	FAO (1986)	General
475-619	Some et al. (2006)	Semi-arid Burkina Faso
596	Molua and Lambi (2006)	Sudano-Sahelian climate, Cameroon
484-575	Durand (2006)	Dry climate region, South Africa
375-575	Giorgis et al. (2006)	Semi-arid Ethiopia
Soybean		
450-700	FAO (1986)	General
605	Molua and Lambi (2006)	Sudano-Sahelian climate, Cameroon
575	Durand (2006)	Dry climate region, South Africa
Onions		
350-550	FAO (1986)	General
183-219	Durand (2006)	Dry climate region, South Africa
Pepper		
600-900	FAO (1986)	General
288	Bonachela et al. (2006)	Mediterranean climate (greenhouse condition)
422-824	Möller and Assouline (2007)	Arid Israel (screened and field conditions)

The large differences between estimated ET_c from this study and those reported elsewhere for some of the crops may be attributable to variations in climatic conditions, availability of water supply, length of crop growth, definition of crop evapotranspiration used, and crop yield.

4.4.4 Physical water productivity

Field level

Water productivity was estimated for Tono and Dorongo at field level (Table 4.9). Generally, WP was higher at Dorongo than at Tono for all WP indicators. At Tono, average values of WP_T, WP_{ETa}, WP_{ETc} and WP_I were 1.21, 1.00, 0.96 and 0.62 kgm^{-3}, respectively, while at Dorongo these were 3.67, 2.65, 2.58 and 2.56 kgm^{-3}, respectively. At Tono, plot1 had a higher WP for all WP indicators while at Dorongo, highest values for WP_T and WP_{ETa} were measured in plot2 followed by plot1, plot3 and plot4. WP_{ETc} for plot1 and plot2 were almost equal followed by plot3 and plot4. WP_I was high in plot1 followed by plot3, plot2 and plot4. Overall, WP_T was high in all plots, reflecting the potential of increasing WP by reduced evaporation of soil moisture from the fields through good management practices. WP_{ETa} was higher than WP_{ETc} in most plots at the two sites except for plots 1 and 3 in Dorongo, because simulated ET_a for these plots was lower than estimated ET_c and actual irrigation. In the remaining plots, WP_I was the lowest at the two study sites. Low values of WP_I at Tono compared to Dorongo were a result of a large quantity of applied irrigation water. Reducing irrigation to values closer to crop ET through improved field water manangement practices would result in an increase in WP_I. Generally low values of WP at Tono as compared to Dorongo were also due to low crop yield, largely caused by tomato pests and diseases.

Table 4.9: Crop water productivity at field scale

WP/Yield	Tono			Dorongo				
	Plot1	Plot2	Average	Plot1	Plot2	Plot3	Plot4	Average
WP_T (kgm^{-3})	1.52	0.90	1.21	3.90	4.66	3.45	2.66	3.67
WP_{ETa} (kgm^{-3})	1.23	0.77	1.00	2.89	3.41	2.37	1.91	2.65
WP_{ETfc}(kgm^{-3})	1.20	0.71	0.96	2.83	2.82	2.69	1.96	2.58
WP_I (kgm^{-3})	0.70	0.54	0.62	3.75	2.53	2.60	1.36	2.56
Yield (kg)	2080	1300	1690	570	3270	2100	8200	3535

Estimated values of WP mirror reported findings on tomato WP in semiarid SSA under furrow and drip irrigation. Yohannes and Tadesse (1998) obtained average WP_I values of 1.54 and 2.29 kgm^{-3} for tomatoes in semi-arid Ethiopia under furrow and drip irrigation, respectively. Closely agreeing WP_I values ranging from 1.47 to 2.49 kgm^{-3} were estimated in the semi-arid southern highlands of Tanzania under furrow irrigation during the dry season (FAO, 2003). Estimated WP_{ETc} ranged from 1.75 to 2.25 kgm^{-3} (FAO, 2003). Higher values of tomato WP have been reported elsewhere, under both surface and drip irrigation. However, WP values reported from SSA fall far below WP findings reported from other climatic conditions. Hanson and May (2006) obtained seasonal average WP_I and WP_{ETc} values of 11.2 and 13.4 kgm^{-3}, respectively for tomatoes under furrow irrigation in San Joaquin Valley, California, USA. Maximum values under drip irrigation were 18.3 and 23.5 kgm^{-3} for WP_I and WP_{ETc} (Hanson and May, 2006). Kocaman et al. (2002) observed ranges from 16 to 20 kgm^{-3} and from 10 to 21 kgm^{-3} for WP_I and WP_{ETc} under different drip irrigation frequencies under Mediterranean climatic conditions. For loam and clay soils in a similar climate in a fiber-glass tank experiment, WP_I and WP_{ET} values of 8.7 and 8 kgm^{-3} were estimated (Katerji et al. 1998).

Despite the fact that WP values obtained in the present study are within the ranges of reported findings from semi-arid environments, they are very low compared to findings reported elsewhere under both furrow and drip irrigation. A potential exists for improving WP at field level, for example by reducing deep percolation losses, which largely occur as a result of over-irrigation at the beginning of the crop season. In four out of the six study plots, irrigation was above crop water requirement (Table 4.5). Avoiding pre-wetting or soaking of plots before plowing at the start of farming activities can increase WP, although the gains could be offset by added costs for land preparation. Mulching is one among the management options for reducing soil moisture evaporation from exposed soil surfaces of crop planted fields.

Farm and scheme levels

For a meaningful discussion of WP values for grain crops and vegetables (tomatoes and onions), which are harvested while fresh, the physical WP values for the respective crops were converted into equivalent nutritional WP, i.e., the product of physical WP and the nutritional content per kg product (Renault and Wallender, 2000) (Table 4.10). The nutritional content for energy (Kcal), protein and fat per kg defined by Renault and Wallender (2000) are adopted to estimate the nutritional WP.

The WP values at farm and scheme levels are based on ET_c only, since irrigation could not be measured per individual crop. At farm level, grain crops showed higher energy, protein and fat nutritional productivity than tomatoes. Calories nutritional WP was highest for rice, while soybean showed the highest protein and fat contents. With the exception of onions, which showed a higher calorie nutritional WP than cowpea and maize at scheme level, the nutritional WP of other crops was similar to values obtained at farm level. The differences in nutritional WP between scales for similar crops were mainly due to differences in physical WP values, while differences between crops were due to both differences in nutritional contents per unit output and physical WP values.

Table 4.10: Water productivity (nutritional) at farm and scheme levels at Tono

Crop	WP_{ETc} (kg/m^3)	Crop nutritional output per kg			Nutritional water productivity		
		Calories (Kcal/kg)	Protein (g/kg)	Fat (g/kg)	Calories ($kcal/m^3$)	Protein (g/m^3)	Fat (g/m^3)
Farm level							
Rice	0.56	2800	69	7	1568	38.64	3.92
Soybean	0.23	4160	365	200	956.8	83.95	46
Maize	0.20	2738	55	12	547.6	11	2.4
Tomatoes	1.35	184	8	1	248.4	10.8	1.35
Scheme level							
Rice	0.55	2800	69	7	1540	37.95	3.85
Soybean	0.25	4160	365	200	1040	91.25	50
Maize	0.24	2738	55	12	657.12	13.2	2.88
Cowpea	0.14	4160	365	200	582.4	51.1	28
Tomatoes	1.35	184	8	1	248.4	10.8	1.35
Onions	2.66	331	12	0	880.46	31.92	0

At the Dorongo scheme, WP_{ETc} and WP_I for tomatoes were 2.57 and 3.0 kg/m^3 respectively, WP_{ETc} being higher by almost 90% than the value obtained for Tono at scheme level. A higher WP_{ETc} value for tomatoes at Dorongo than at Tono could be attributed to differences in planting dates and crop yield between the two sites. At Tono, an average ET_c for the period from October 2005 to April 2006 was estimated, while at Dorongo, ET_c was the average from mid November 2005 to mid March 2006. A longer crop growth period resulted in a higher ET_c (503 mm) than the slightly lower ET_c (468.4 mm) for Dorongo. Furthermore, average seasonal crop yield at Tono was 6.8 t/ha while at Dorongo it was 12 t/ha.

The difference between WP_{ETc} and WP_I at Dorongo was the result of a deficit in the irrigation supply during the crop season. The deficit in crop ET was most likely offset by root-zone soil moisture capillary rise, which more likely resulted from continuous leakage or seepage of reservoir water.

WP_{ETc} generally exhibit high spatial variability (Table 4.11), mainly due to crop yield and climatic variation (Tuong and Bouman, 2003). Although WP_{ETc} values for rice in this study are low, they fall within general ranges of reported WP values. Lower values of WP_{ETc} for maize, cowpea and soybean as compared to values obtained in this study were reported in Burkina Faso, Niger, Cameroon and Senegal under semi-arid and semi-humid climates (Some et al., 2006; Moussa and Amadou, 2006; Molua and Lambi, 2006; Diop, 2006; Durand, 2006).

Table 4.11: Water productivity of rice, maize, cowpea, soybean, onions and pepper in terms of yield (kg) per m^3 of WP_{ETc} reported in literature

WP_{ETc}	Source	Location
Rice		
0.4-1.60	Tuong and Bouman (2003)	Literature under Asian field conditions
0.51	Ahmad et al. (2004)	Pakistan
0.94	Singh (2005)	India
1.08	Zwart and Bastiaanssen (2003)	Review of 82 publications of the last 25 years
0.15-0.60	Cai and Rosegrant (2003)	Global averages based on 1995 production scenarios
Maize		
0.59-0.71	Giorgis et al., (2006)	Ethiopia
0.40-0.70	Igbadun et al. (2006)	Tanzania
0.11-0.34	Some et al. (2006)	Burkina Faso
0.24	Diop (2006)	Senegal
0.14	Durand (2006)	South Africa
0.12	Molua and Lambi (2006)	Cameroon
Cowpea		
0.08-0.11	Some et al. (2006)	Burkina Faso
0.01-0.04	Moussa and Amadou (2006)	Niger
Soybean		
0.13	Molua and Lambi (2006)	Cameroon
Onions		
3.83-5.96	Durand (2006)	South Africa
Pepper		
1.5-80	Möller and Assouline (2007)	Israel

Low values of WP for maize, cowpea and soybean in the current study could be attributed to low crop yield due to poor crop timing, excessive water application, and poor field crop management. WP_{ETc} could be improved through better management practices such as correct crop timing in the season, proper supply of irrigation water, improved seeds and correct application of chemical inputs. At scheme level, WP can be improved by minimizing non-beneficial depletion at Tono, which accounted for about 71% of the irrigation water supply. However, at Dorongo, which appeared to be more water-use efficient, only a limited non-beneficial depletion to which WP could be capitalized was observed, WP improvements should be directed towards factors that enhance crop yield, such as control of pests and diseases, better crop varieties and crop timing, and correct use of fertilizers (Bationo et al., 2006; FAO 2001; Kouka et al., 1995).

4.4.5 Summary and conclusions

The following conclusions are drawn based on soil water balance and physical water productivity analysis at plot, farm and scheme levels at Tono and Dorongo for the 2005/06 dry season:

- SWAP was calibrated and validated successfully by linking the model with PEST to optimize parameters α and n of the soil hydraulic PTFs. The parameters were effectively optimized, and the ME and RMSE, characterizing observed vs simulated soil water content at different soil depths, were fairly good.
- Most of the plots were over-irrigated by 40 to 70% at Tono and by 11 to 40% at Dorongo. As a result, Q_{bot} was higher in the Tono plots as compared to Dorongo, with average values of -340.7 and -38.8 mm at the two sites, respectively. Percolation losses at field level could be reduced by avoiding soaking of plots, which is generally done to facilitate easier plowing at the beginning of the season. This accounted for up to 40% of the irrigation water in some of the plots. Plot3 at Dorongo that was plowed without soaking showed the lowest seasonal Q_{bot} (-6.2 mm). At Dorongo, part of the crop water requirements at the upstream plots close to the reservoir was contributed by capillary rise of soil moisture to the crop root zone. However, the contribution of soil moisture could be a result

of leakage and seepage of reservoir water, and not from soil moisture stored during the previous season. The SWAP model accurately simulated soil water balances at plot level.

- Irrigation supply was 3-times higher than ET_c at farm level at Tono, and more than 60% of the irrigation appeared as losses through surface drains (SD), percolation to groundwater and non-beneficial evaporation ($Q_{\text{bot+nb}}$) from uncropped fields. Although SD and $Q_{(\text{bot+nb})}$ were considered to be losses at farm level, they may not be true losses at scheme level if recovered and reused downstream in the scheme. However, since farm drainage flows to the main course of Tono River, reuse entails additional costs of pumping water out from the river channel. Because of these pumping costs, only a few farmers use pump irrigation along the river channel at Tono, mainly for irrigating tomatoes.
- Crop water use was only 17% of the irrigation supply at scheme level at Tono. 71% of irrigation supply was consumed by non-crop vegetation, deep percolation losses and through open surface evaporation ($Q_{\text{bot}} + E_{\text{nb}}$). Out of the 71%, about 13% was used for land preparation and for maintaining a water layer in the rice fields, and 28% was utilized by non-crop vegetation. The remaining 30% was lost through percolation losses to the ground, and as a result, seasonal crop water-use efficiency was only 16% for Tono, as compared to more than 100% for Dorongo. A significant improvement in water use efficiency for Tono could be achieved by reducing the 71% non-beneficial depletions at scheme level through concentrating farmers in selected farms for easier control of irrigation water in contrast to the existing practice of spreading farmers all over the scheme at the expense of inefficient water distribution.
- Water productivity was lower at Tono than at Dorongo at plot level. Although the WP values obtained in this study concurred with other findings from semi-arid SSA, the values were far below average values for similar irrigation methods under different climatic conditions. A potential exists for improving WP at field level, for example by reducing deep percolation loses, which largely occurred as a result of over-irrigation at the beginning of crop season. WP could also be improved through plot management practices such as mulching, which

reduces direct soil moisture evaporation from the exposed soil surface between the crop rows and plants that does not contribute to crop production.

- WP_{ETc} can be improved through better management practices, such as good timing of crop establishment within the season, correct and reliable supply of irrigation water, improved seeds, and proper and correct application of chemical inputs. At Tono, efforts to improve WP should focus on minimizing non-beneficial depletion, which accounted for more than 70% of the irrigation water supply at scheme level. However, there is not much hope for WP improvement based on water management per se at Dorongo. Instead, strategies should be directed towards factors that enhance crop yield, such as control of pests and diseases, improved crop varieties, better crop timing, and correct use of fertilizers.

5 THE VALUE OF IRRIGATION WATER FOR TOMATOES

5.1 Introduction

Physical water productivity (WP) is a useful metric for identifying levels of water system performance and potential strategies for improved water management. However, the contribution of non-water input factors in irrigated agriculture, which are also important for WP improvement, are not always explicit in the physical WP expressions. Guerra et al. (1998) and Wichelns (2002) emphasize the importance of considering other factors such as labor, capital and management in the assessment of strategies for improving the value of water. The knowledge of factors contributing to the total value of production apart from water is, therefore, important for understanding the value of water in irrigated agriculture.

Generally, the natural resource valuation concepts are used to quantify the value or benefits of water in different water uses. In the analysis of river basin water resources, the contribution of water to the total value of production in equivalent monetary terms is used to infer economic WP or economic value of water. Although the economic value of water use may be defined by its opportunity cost (Kijne et al., 2003), prices of goods and services received and paid by farmers (farm-gate transactions) may be used to estimate the value of water. This value would for example, show the impact of water use at farm level (Bakker et al., 1999). The opportunity cost of irrigation water would be, for example, the benefits foregone if the same water could be used for running turbines to generate electricity to supply economic activities. Several methods exist for estimating the value of water. According to Agudelo (2001), the majority of water valuation methods can be categorized into three major groups: 1) methods based on water markets such as sales or rentals of water rights and land, 2) methods that value water as an intermediate good such as producers' water demand function, residual value imputation, value added and alternative cost methods, 3) and methods that value water as a final good. The choice of the method will depend on the purpose of the valuation exercise, availability of data, resources and time. Marginal and partial factor productivity are some of the common indicators when quantifying the economic value of water and other natural resources based on production functions (Dawe and Dobermann, 2002). Marginal productivity is defined as the rate of change of the total product for a unit change in the production factor of interest, whereas partial factor productivity (PFP) is the overall or average productivity attributed to a single factor (Beattie and Taylor, 1985). The derivations of the marginal value of water require the specification of a water demand function or production function. For irrigated agricultural crops, the functions can be derived directly from experiments and statistical analysis of secondary data. Water production functions can also be indirectly estimated by simulation models (Young, 1996, Ward and Michelsen, 2002). Although production functions based on experimental observation are considered more realistic and reliable than the production functions based on statistical and simulation models, most of the experimental observations are expensive and time consuming and cannot be generalized to environmental conditions different from the experimental conditions (Ward and Michelsen, 2002). However, where water supply and crop growth parameters can be obtained, the generation of production functions using simulation models is a more feasible approach (Young, 1996).

The residual imputation, a method for valuing water as an intermediate good, is commonly used for determining the value of water in irrigation. The method is applied based on two primary postulates (i) producers maximise profit by adding productive inputs until the point where the value of marginal productivity equals the marginal cost of inputs, and (ii) the total value of production can be divided into shares such that when each factor is paid according to its marginal productivity, the total value of production is completely exhausted (Young, 1996). When all the factors of production and corresponding cost are taken into account, the total economic value of services and goods can be estimated (Renwick, 2001). Including all necessary factors of production in the production function is important to avoid estimation biases in the residual value (Young, 1996). The change in net income under the scenario with versus without irrigation and optimization (mathematical programming and dynamic optimization) are the main two variants of the residue method (Young, 1996; Agudelo, 2001; FAO, 2004). However, mathematical programming and dynamic optimization require detailed data on the agents optimized (Agudelo, 2001). For a short-time or seasonal analysis, such detailed data may not be readily available, which restrict their applicability.

Although estimation of the marginal value of water using production functions could have been a suitable approach for this particular study, the present data do not support construction of production function for which the condition of marginality can be derived. The main limitation is the lack of the quantity of water supply for a sufficient number of farming plots within the season, although non-water input production factors are well captured. Additionally, secondary data on crop water supply and production factors are virtually non-existent for the study area. The residual method is, therefore, employed to estimate the value of water for dry season irrigated tomato farming. The estimation is done under the following assumptions: (i) tomatoes is a high value crop, among those to which Young (1996) refers as specialty crops for which the method can be applied, (ii) a short-term (seasonal) analysis for the residual value is applied for which some of the fixed capitals can be excluded from the inputs, (iii) production inputs and outputs are reasonably captured, thus avoiding over-/or under-estimation of the residue value of water, and (iv) farm-gate prices of goods and services reflect existing local market conditions.

Justification for the choice of tomatoes as a study crop

Tomatoes, onions, pepper, and leaf vegetables are the main crops produced in the UER during the dry season. Tomatoes and onions typically cover a large percentage of the area irrigated during the season. Overall, tomatoes occupy the largest dry season irrigated area when the area under medium (Tono and Vea) and small reservoirs is combined (Figure 5.1-A). However, considering only the small reservoirs, the average area under onions is about four times larger than that under tomatoes (Figure 5.1-B). Tomatoes have long been perceived as the most lucrative crop in the UER, and more than 50% of the dry season irrigators produce tomatoes. High yields per unit area make tomato farming more attractive than onion farming, although the available MOFA records on the area cultivated and on yield/ha are contrary. For example, when the seasonal production on medium and small reservoirs is combined land productivity was higher for tomatoes than for onions in 2000/01 and 2002/02 (Figure 5.1-C). However, considering production in small reservoirs only, yield/ha for onions was higher than for tomatoes (Figure 5.1-D).

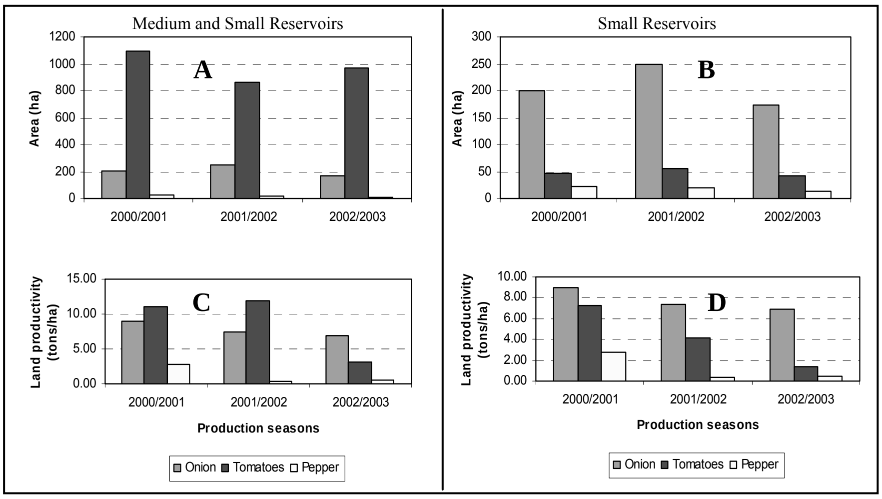

Figure 5.1: Area (ha) and land productivity (tons/ha) for irrigated onions, tomatoes and pepper in the UER (Data source: various reports, MOFA, Bolgatanga)

While onions have the advantage of increased storage life and returns to market if properly dried, stored and sold during a good market, many farmers still believe that tomatoes are more profitable than onions despite the fact that it is a highly perishable good. For comparison between two contrasting irrigation systems i.e., medium and small reservoirs irrigation schemes under a similar crop, tomatoes were selected as a study crop, although technically, onions would have been more appropriate.

5.2 Data collection and methodology

5.2.1 Sampling procedures and questionnaire survey

A semi-structured questionnaire for the farmers was designed and interviews conducted to elicit information on general farming household characteristics and dry season water use for irrigated tomato farming. The questionnaire was administered to a sample of 120 farmers between March and April during the 2005/06 dry season. Sample farmers were selected based on a stratified random sampling approach from a list of participating farmers, 50% of the total sample was from Tono and 50% from Dorongo. At Tono, the sample was drawn from the list of farmers obtained from the Tono project manager's office. At Dorongo, farmers list created during the measurements of their plots was used to select the sample. Sampling ensured representation of farm location in schemes, irrigation methods, and periods of planting. Local enumerators who spoke both the local and English language were engaged and trained to enumerate the questionnaires.

Interviews were carried out on the farmers' homestead compounds. Completed questionnaires were coded and entered into the SPSS statistical package version 14.0.

5.2.2 Estimation of farmer's capital from agricultural assets

Information on important agricultural assets was extracted from the survey data and used to estimate seasonal farmers' capital assets. An economic life span of five years was assumed for most agricultural assets such as hand hoes, shovels, cutlasses, rakes, pickaxes and watering cans. The agricultural asset price index (API) was constructed for a period of five years from 2000 to 2005 based on reported purchase prices using 2000 as the base year. The purchase price for each asset was uniformly depreciated over the assumed lifespan, and current values of the assets were estimated as a product of API for the year in question and the distributed purchase price. A 10-year lifespan was assumed for agricultural assets such as tractors and tractor-drawn implements, irrigation pumps, oxen/bullock-drawn plows, and pulling carts. These assets were owned by only a few farmers, so that construction of API was not feasible because of their discontinuous purchase periods. The Sum-of-Years Digits, a depreciation method, which results in a more accelerated asset write-off during its initial years of use, was arbitrarily chosen to estimate current values of the assets using a salvage value of 20% of the asset's purchase price. Since these assets were owned by a few farmers only, seasonal depreciation of an asset was used to represent invested capital into irrigated farming to avoid distortions of mean capital for each study site. For agricultural assets that existed beyond their assumed lifespan, the actual life of the asset was used. Total asset values were estimated and used as equivalent capital for the current crop season.

In the UER, the land that is used for farming is not rented for a fee but rather borrowed. Fixed water levies per hectare paid by every participating farmer at the two sites were therefore used as a substitute (proxy) for the value of land. This was done in order to avoid over-estimation of the derived value of water, although the true value of land could be higher than the proxy value.

5.2.3 Labor usage and charge, machinery hire and farming inputs

Reported working hours for different farm operations were converted to equivalent mandays. The working hours for children and women laborers were multiplied by 0.5

and 0.75 respectively (Ruthenberg, 1980) to obtain equivalent mandays. A labor charge of ¢10,000 (1.11US$), commonly paid to hired laborers for farming activities was used to estimate the cost of labor use for all farming activities, except for harvesting at Dorongo where laborers were paid ¢5,000 (0.55US$). Similar rates were applied for family, communal and exchange labor, which were common at Dorongo, and for harvesters paid in kind by collecting non-marketable harvested tomatoes. Available rental rates for agricultural machinery from machinery operators, and purchase of inputs such as seeds and agro-chemicals reported by farmers were used to estimate the cost of farming inputs. Reported quantities and costs of inputs from the sample survey were triangulated with unit prices of related input materials collected from retailers in the UER and, where necessary, adjustments of reported quantities and costs was done to reflect reasonable input usage given known plot sizes.

5.2.4 Total revenue, return to management and data analysis

The farm-gate prices of harvested crops were used to estimate the revenue during each harvesting turn. The total revenue for each farmer was estimated by summation of the revenues obtained from the number of harvests per season. Non-marketed, low-quality tomatoes were not included in the total value of production, since they represented only a minor fraction of the total harvest and were collected by laborers instead of payment. Five percent of the gross revenue was assumed to represent return to management (Young, 1996). Processed data were analyzed for frequencies, descriptive statistics and the mean difference (T-test) for the value of water using SPSS.

5.2.5 Value of irrigation water

For a single product of tomatoes, *Y*, produced by the factors of production: capital (K), labor (L), other inputs (Z) and water (W), the production function can be written (Eq. 5.1):

$$Y = f\left(K, L, Z, W\right) \tag{5.1}$$

Assuming competitive factor and product markets, prices may be treated as constants (constant returns to scale). By the second postulate of the residual imputation method (Eq. 5.2) can be written:

$$TVP_Y = \sum_{i=j}^{N} VMP_i Q_i \tag{5.2}$$

Where: TVP is the total value product Y, VMP_i and Q_i are the value marginal product and quanties of resource from i =j to N number of marginal products and quanties of resources respectivelz.

The first postulate of the residual method, which states that P_i = VMP_i allow replacement of P_i into (Eq. 5.2), which after rearranging gives (Eq. 5.3):

$$TVP_Y - \sum_{i=j}^{N} P_i Q_i = P_w Q_w \tag{5.3}$$

When all the variables in (Eq. 5.3) are known, the unknown P_W can be solved to impute the value of the residual claimant (water) P_W (Eq. 5.4):

$$\frac{TVP_Y - \sum_{i=j}^{N} P_i Q_i}{Q_w} = P_w \tag{5.4}$$

5.3 Results and discussions

5.3.1 Irrigation farming inputs

Plot-size allocation

Plots allocated for irrigation in the UER are generally small. For small reservoirs, average plots for dry season irrigation vary between 0.12 ha and 0.4 ha per household (Bacho and Bonye, 2006). Average plot sizes ranging from 0.2 to 2 ha have been reported at the Tono and Vea irrigation schemes (Dittoh, 1998). However, much smaller plot sizes (<0.2 ha) were observed during the current study. Although designated plot sizes for upland crops, for example at Tono, are up to 1 ha on average, majority of farmers are unable to farm entire plots, and large plots are commonly shared by a number of farmers who also share the water levy and the costs of machinery for land preparation. At Tono, about 17% of the respondents had plots smaller than 0.4 ha, while 73% farmed plots varying from 0.4 to 1.42 ha (Table 5.1). Only 10% of the respondents were allocated plots larger than 1.42 ha. At Dorongo, 28% of the sampled farmers had plots smaller than 0.08 ha, and 62% farmed plots varying from 0.09 to 0.28 ha. Only 10% of the farmers were allocated plots larger than 0.28 ha (Table 5.1). Only a few farmers (10%) had plots larger than 1.0 and 0.3 ha at Tono and Dorongo, respectively. Average plot size was 0.7 ha and 0.2 ha at the two sites, respectively.

Table 5.1: Distribution of irrigated plots at Tono and Dorongo

Tono		Dorongo	
Plot size (ha)	% of farmers	Plot size (ha)	% of farmers
<0.4	17	<0.08	28.3
0.4-1.42	73	0.09-0.28	61.7
1.43-2.44	5	0.29-0.49	6.7
2.45-3.47	3	0.5-0.69	3.3
>3.48	2	Total	100
Total	100		

Irrigation methods and fuel use for pump irrigation

The majority of plots used surface canal irrigation, both at Tono and Dorongo (Figure 5.2). At Tono, only 7% of the respondents used pumps to irrigate, and 3% had plots that were irrigated with both surface canal and pumps. The remaining 90% of the farmers irrigated their plots using surface canals. Similarly, at Dorongo, 68% of the plots were irrigated with surface canals, while 22% and 10% used pumps and a combination of surface and pump irrigation, respectively. The large number of pump users at Dorongo than at Tono was mainly due to the pump sharing practice among the farmers and did not represent an increased number of pump owners. Mean fuel use for pump irrigation was 61.7 and 72 l/ha at Tono and Dorongo, respectively (Tables 5.2 and 5.3). The mean fuel use was homogeneous between the study sites, since only a few farmers could afford pump-irrigated plots.

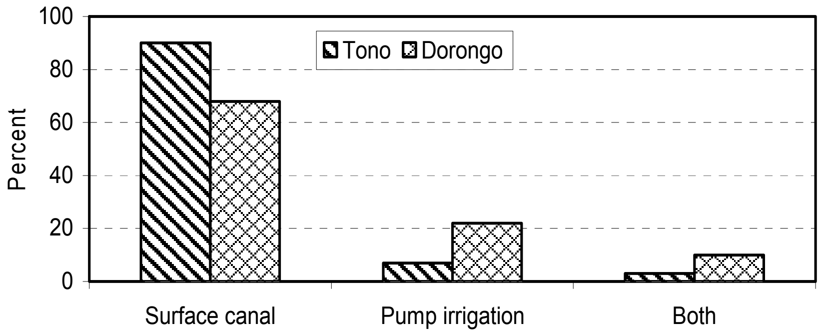

Figure 5.2: Plot irrigation methods

Table 5.2: Farming inputs at Tono

Input	N	Mean	Median	s.d.	Min.	Max.
Plot size (ha)	59	0.75	0.40	0.78	0.04	4.50
Fuel use (l/ha)	5	61.75	66.67	37.83	21.43	105.63
Seed use (kg/ha)	58	0.20	0.20	0.05	0.10	0.25
Fertilizer use (kg/ha)	58	472.79	500.00	154.25	200.00	833.33
Pesticides (kg or l/ha)	57	4.04	3.13	2.25	1.23	10.00

Table 5.3: Farming inputs at Dorongo

Input	N	Mean	Median	s.d.	Min.	Max.
Plot size (ha)	60	0.16	0.13	0.13	0.03	0.69
Fuel use (l/ha)	18	72.45	78.37	21.12	28.91	100.84
Seed use (kg/ha)	60	0.24	0.25	0.04	0.14	0.29
Fertilizer use (kg/ha)	60	495.43	500.00	68.73	200.82	606.41
Pesticides (kg or l/ha)	60	4.08	4.06	1.57	1.01	8.11

Seeds, inorganic fertilizer and pesticide application

The tomato variety Petomech VF is the preferred variety at both sites, followed by a combination of Petomech and a no-name variety at Tono, and only a no-name at Dorongo (Table 5.4). The remaining varieties all together constituted 7% and 23% of variety use at Tono and Dorongo, respectively. The reasons underlying variety preference by the farmers are not clearly understood, though they could be closely linked to quality, lifespan of harvested tomatoes, and resistance to pests and diseases. The average seed use was 0.20 kg/ha and 0.24 kg/ha at Tono and Dorongo respectively (Tables 5.2 and 5.3). The large spread for seed use among farmers could be due to the few sampled farmers with slightly higher seed rate application (25% of the sample, both at Tono and Dorongo), and the difficulty in estimating seed requirement for farmers with smaller plots, because the seeds are purchased in packages (100 grams) from retailers irrespective of plot size.

Table 5.4: Common varieties of tomatoes planted in the study area

Variety	Tono			Dorongo		
	Frequency	%	Cumulative %	Frequency	%	Cumulative %
Petomech VF	52	86.7	89.7	33	55.0	55.0
Rfuego	1	1.7	91.4			
No-name				13	21.7	76.7
Petomech and no name	2	3.3	94.8	3	5.0	81.7
Petomech and Tropimech	1	1.7	96.6	5	8.3	90.0
Tropimech/no name	1	1.7	98.3	1	1.7	91.7
Tropimech				5	8.3	100.0
Petomech and ST Louis	1	1.7	100.0			
Total	58	96.7		60	100.0	

The use of organic manures in the UER is confined to rain-fed compound plots close to the farmers' homesteads. Insufficient quantities of organic manure and lack of transport for bulk quantities to distant locations constrain the use of organic manure on irrigated plots (Yilma, 2005). Inorganic fertilizers are the main types of fertilizers used on dry season irrigated plots. A combination of NPK (15:15:15) and Sulphate of Ammonia (SA) is applied by the majority of tomato farmers in the UER, with a varying number of applications per season depending on the farmers' financial abilities. At Tono, all respondents applied chemical fertilizer twice during the season, while at Dorongo 90% applied twice and the remaining 10% once or three times per farming season. The mean fertilizer application was 472.8 kg/ha and 495.4 kg/ha at Tono and Dorongo, respectively (Tables 5.2 and 5.3). Although the amount of fertilizer was uniformly distributed between sites, application rates were slightly higher at Dorongo as indicated by the mean and median (Table 5.2). The slightly increased fertilizer application rates at Dorongo in comparison to Tono further underscore the problem of purchasing and applying correct quantities of inputs on small plots as highlighted above. Following soil surveys at the Tono and Vea schemes in 1988, the Soil Research Institute recommended application rates of 50, 120, and 120 kg/ha for N, P_2O_5, and K_2O, respectively for irrigated tomato farming (Thalm, 1988). From the survey data, the majority of farmers apply equal amounts of NPK and SA. With the average fertilizer use (Tables 5.2 and 5.3), the application rates are estimated at 89, 37, and 37 kg/ha for N, P_2O_5, and K_2O, respectively. Although N is applied in excess of the recommended rate, P_2O_5, and K_2O application is far below recommended rates, and the majority of soils in the UER contain available P and available exchangeable K below the critical ranges (Thalm, 1998). Undoubtedly, the application of unbalanced quantities of fertilizers could have negative effects on the uptake of nutrients by crop plants resulting in lower crop yields than would be obtained if the nutrient proportions were balanced.

The presence of pests and diseases in tomato crops demands a high application of pesticides. Common pests include nematodes, amphids, whitefly and caterpillar, while early and late blight, fusarium, bacterial wilt, and fruit rot are the major tomato diseases (Asare-Bediako et al., 2007). Pesticides are commonly applied in combination with foliar fertilizers such as Harvest-more, Cropmax and NPK (19:19:19). Most of the pesticides are believed to be derivatives of Dichloro-Diphenyl-Trichloroethane (DDT), which is available under various trade marks (Table 5.5). The chemicals are applied in liquid form by spraying using manual chemical applicators such as knapsack sprayers after mixing with the desired quantities of water.

Table 5.5: Brands of pesticides and foliar fertilizers applied in the study area

DDT Brands reported as insecticides	DDT Brands reported as fungicides	Commonly applied foliar fertilizers
PAWA 2.5EC	Diothine	Harvest-more
Karate	Saiden Supper	NPK 19:19:19
Supton	Coside	Cropmax
Super force/Grow force	Champion	
Tireness	TOPSON/W10	
	Diosere/ Dioxin	

Pesticide application varied from 1.23 to 10.0 kg or l/ha with mean and standard deviation of 4.04 and 2.25 kg (or l/ha) at Tono, while at Dorongo pesticides use varied from 1.01 to 8.11 kg/ha (or l/ha) with mean and standard deviation of 4.08 and 1.57 kg/ha (or l/ha) (Tables 5.2 and 5.3). Although mean pesticide use was almost the same between the two sites, the number of applications varied within the schemes. About 82% of the respondents applied fungicides twice or three times at Tono, while at Dorongo the majority (78%) applied three times or more per farming season (Figure 5.3). At both sites, the majority of the farmers applied insecticides three times or more due to high incidence and severity of pests and diseases.

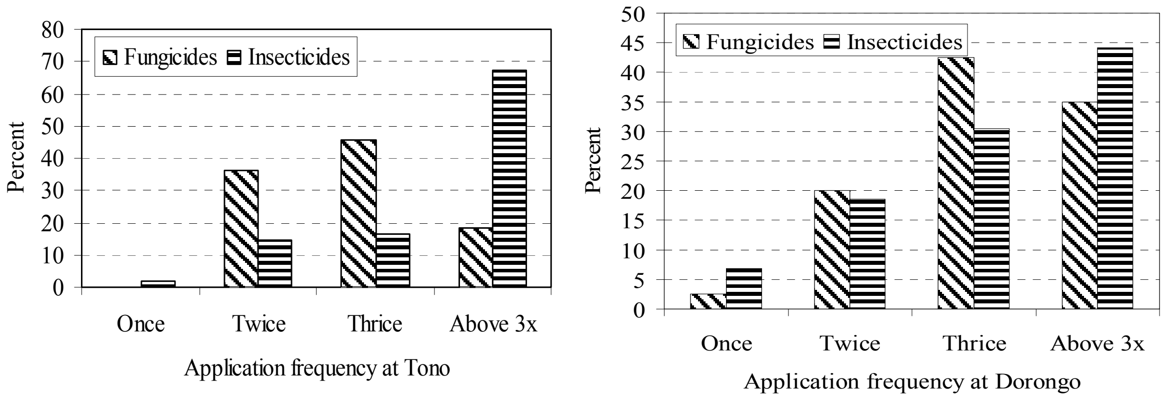

Figure 5.3: Pesticide application in Tomato at Tono and Dorongo

5.3.2 Cost of production

Land and capital (agricultural assets)

In the UER, land is collectively owned by the communities and vested in the Tendana, the traditional priest (king) who is regarded as the custodian of the land and performs sacrifices related to land (Bacho and Bonye, 2006). Irrigable lands in small reservoirs were originally owned by families or traditional chiefs who agreed to share the land with community members during the dry season after the construction of the reservoirs. Most of the families or traditional chiefs willingly offered the land occupied by the reservoirs without compensation. Therefore, irrigated lands in most of small reservoir areas are family owned, and the land is only transferred to the WUAs during the dry seasons, which in turn redistribute it to the members of the WUAs. The land is returned to the owner families during the rainy season. Generally, land can be allocated to any family member in the community as long as the family remains in the community.

Allocated land cannot be sold or transferred to other families without the knowledge of the Tendena (Bacho and Bonye, 2006). Therefore, land is not rented for a fee in the UER but can be borrowed for a particular farming season.

The production capital, both at Tono and Dorongo, mainly constitutes common implements and tools used for farming activities such as hand hoes, cutlasses, shovels, pickaxes, rakes, watering cans/buckets, and knapsack sprayers (Tables 5.6 and 5.7). It also includes depreciation of agricultural assets such as irrigation pumps, pulling carts, ox-plows, tractor implements and tractors. The depreciated value of expensive capital assets for the farming season in question was used to minimize distortions of the mean capital between the sites occurring because a few farmers had high-value farming implements. The mean capital at Tono was twice that at Dorongo. Although minimum capital between the sites was similar, maximum capital at Tono was about four times that at Dorongo, indicating more-capital diverse farmers at Tono than at Dorongo.

Table 5.6: Cost of farming inputs per ha at Tono

Variable		Mean	Median	s.d.	Min.	Max.
		(x 1000)				
Capital (cedis)	60	252	106	504	7	3595
Seeds (cedis/ha)	58	210	210	53	100	275
Fertilizers (cedis/ha)	58	1702	1800	555	720	3000
Pesticides (cedis/ha)	57	364	325	197	111	750
Fuel (cedis/ha)	5	497	537	305	173	850
Plowing (cedis/ha)	56	500	500	0	500	500
Water levy (cedis/ha)	58	548	548	0	548	548

Table 5.7: Cost of farming inputs per ha at Dorongo

Variable	N	Mean	Median	s.d.	Min.	Max.
		(x 1000)				
Capital (cedis)	60	133	90	136	7	781
Seeds (cedis/ha)	60	247	254	36	142	306
Fertilizers (cedis/ha)	60	1947	1796	1220	1283	11083
Pesticides (cedis/ha)	60	405	389	145	121	894
Fuel (cedis/ha)[+]	18	507	549	148	202	706
Plowing (cedis/ha)	38	441	500	100	250	500
Water levy (cedis/ha) *	60	200	200	0	200	200

[+]*All pumps are assumed to use petrol as fuel; price during the time of the study was 7000 cedis/l, * Proxy value of land*

The cost of seeds, fertilizers, pesticides and fuel (for pump-irrigated plots) was uniformly distributed among farmers within the study sites, although higher costs were obtained for Dorongo. The higher per-hectare costs of seeds, fertilizers and pesticides at Dorongo reflect application of these inputs in large quantities, a problem associated with the difficulty in estimating the correct or required amount of inputs for small plots (<0.1ha). Although only 7% and 22% of the sampled farmers used pump-irrigated plots at Tono and Dorongo, respectively, mean fuel cost did not differ much between the two sites. The slightly increased costs of fuel use at Dorongo could be due to the greater distance between the water source and irrigated plots, which varied between 0.1 and 0.5 km as compared to a distance of within 0.1 km at Tono. The pumping distance further increased as the drawdown of the water level in the reservoir increased.

Tractor (T), oxen/bullocks (O/B) and human labor (HL) or a combination of the three were the most common plowing methods for irrigated plots. At Tono, only 3% of the respondents used human labor while 97% used tractors to plow their plots (Figure 5.4). At Dorongo, the distribution of plowing methods was 37% for human labor, 12% for oxen or bullocks, 45% for tractor, 2% for a combination of human labor, oxen and tractor (HL/O/T), and 5% for a combination of oxen or bullock and tractor (O/B/T).

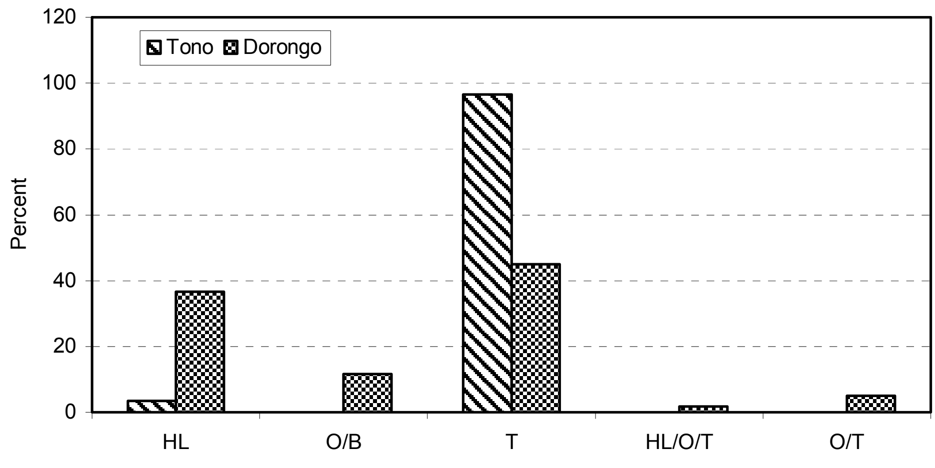

Figure 5.4: Plowing methods for irrigated plots at Tono and Dorongo

At Tono, the cost of tractor plowing during the study period was 500,000 ¢/ha (55US$/ha). Although tractor-and oxen- or bullock-plowing at Dorongo were charged based on the size of a plot, a mean value of 441,000 ¢/ha (49US$/ha) was estimated.

Generally, when human labor was used, ridges were directly constructed without tilling the land. At Tono, hired labor was common, while family, communal or exchange labor were common at Dorongo and the costs involved for labor use were associated with buying of food and drinks for the laborers. Therefore, where human labor was used for land preparation, the costs involved are included in the cost of labor as described in the section on labor and cost of labor. The water levy was about 548,000 ¢/ha (61US$/ha) and 200,000 ¢/ha (22US$/ha) at Tono and Dorongo, respectively.

Labor and cost of labor

The mean total labor use was 80.6 man-days/ha at Tono, while at Dorongo it was 77.3 mandays/ha (Table 5.8). The labor use for irrigating and harvesting was about 46% and 45% at the two sites, respectively. Irrigating is a labor-intensive activity because of the method used, which involves directing, ponding and blocking water between the furrows of the ridges sequentially one after another. Harvesting is an equally labor-intensive activity, because tomatoes are handpicked and sorted. Harvesting may occur several times before the final harvest, depending on the readiness of the tomatoes for harvesting and availability of markets. Land preparation, transplanting, weeding and mulching are other labor-intensive activities, all constituting about 43% and 45% of total labor use at Tono and Dorongo respectively. Although machinery are used for land preparation at Tono in particular, they are expensive and mainly limited to plowing. Harrowing and ridging are commonly done manually, thus requiring more human labor. Few farmers apply mulching, and the associated labor mainly involves sourcing of mulching materials used to cover tomato plants. The remaining activities, i.e., nursery raising, fertilizing, pesticide application and lifting of plants require less labor, all together accounting for 11% and 10% of the total labor use at the two sites, respectively.

Table 5.8: Labor use (man-days/ha) and labor cost (¢/ha)

Activity	Tono					Dorongo				
		Labor use		Labor cost			Labor use		Labor cost	
	N	Mean	s.d.	Mean	s.d.	N	Mean	s.d.	Mean	s.d.
				(x 1000)					(x 1000)	
Nursery preparation	58	3.62	0.95	36	9	60	3.37	0.49	34	5
Land preparation*	58	10.60	2.28	106	23	60	10.39	3.97	104	40
Transplanting	55	7.26	2.13	73	21	60	9.49	2.63	95	26
Irrigating	58	18.80	3.47	188	35	60	18.71	3.85	187	39
Fertilizing	58	4.42	0.82	44	8	60	4.40	0.91	44	9
Weeding	58	9.40	1.73	94	17	60	9.35	1.93	94	19
Pesticides appl.	56	1.44	0.28	14	3	57	1.45	0.38	15	4
Lifting of plants	57	4.50	0.86	45	9	49	4.47	1.09	45	11
Mulching	20	7.31	3.30	73	33	2	5.45	1.46	54	15
Harvesting	58	18.54	4.11	185	41	60	16.33	3.51	82	18
Total labor use	58	80.60	9.14	806	91	60	77.27	10.22	691	99

**Include: land clearing, soaking, plowing, harrowing, and ridging*

The mean total labor cost was 806,000¢/ha (89.3US$/ha) and 691,000¢/ha (76.5US$/ha) at Tono and Dorongo, respectively. The mean costs of labor for irrigating and harvesting together were about 46% (Tono) and 39% (Dorongo) of the mean total labor costs. The low labor costs for the two activities at Dorongo as compared to Tono were due to the reduced labor charge per manday for harvesting, which was 50% of that paid at Tono. The cost of labor for land preparation, transplanting, weeding and mulching together was about 43% (Tono) and 50% (Dorongo). Labor cost for the remaining activities (nursery preparation, fertilizing, pesticide application, and lifting of plants) contributed to about 11% of the mean total labor cost at both sites.

The mean labor cost for most activities was similar between the two sites except for transplanting, which was slightly higher at Dorongo, and for mulching and harvesting, which was higher at Tono. The slightly higher cost for transplanting at Dorongo was due to increased labor use for the activity, which was about 9.45 man-days/ha compared to 7.27 man-days/ha at Tono. Increased labor use at Dorongo for transplanting could be attributed to the use of family and communal labor in most farming activities, increasing the number of laborers per farm operation and hence the labor use and cost. Labor costs for nursery preparation, mulching and harvesting were more variable at Tono as compared to Dorongo, while the variability of labor cost for land preparation, transplanting, irrigating and plant lifting was higher at Dorongo than at Tono. Labor costs for fertilizer application, weeding, and application of pesticides were not significantly different at the 5% significance level between the two sites. Although many farmers use hired labor at Tono, a combination of family, communal and exchange labor is common at Dorongo, and when valued at the labor market rate in the study area, the difference in labor use and cost between the two study sites is minimized.

5.3.3 Crop yield, inputs contribution and economic returns to water

The maximum yield at Tono was twice the maximum yield at Dorongo (Table 5.9). Yield ranged from 1.45 to 83.49 tons/ha at Tono and from 1.95 tons/ha to 41.91 tons/ha at Dorongo. The lower mean total revenue at Tono was less by 54% compared to that at Dorongo. However, maximum revenue at Tono was slightly higher compared to that at Dorongo, reflecting a few cases of higher yield at Tono. The total revenue per hectare ranged from 2.03 to 129.5 million cedis at Tono and from 3.12 to 104.83 million cedis at Dorongo. Both yield and total revenue were more variable at Tono compared to Dorongo. The variability could have been influenced by many factors, such as levels of inputs, effects of pests and diseases, crop timing and market fluctuations for harvested tomatoes.

Table 5.9: Crop yield, total revenue and per hectare share of production inputs

Variable	Tono					Dorongo				
	N	mean	s.d	min	max	N	mean	s.d	min	max
Yield (tons)	58	15.93	15.53	1.45	83.49	60	11.96	8.69	1.95	41.91
Total revenue (million ¢)	58	24.41	25.26	2.03	129.50	60	23.13	21.38	3.12	104.83
Capital (million ¢)	58	2.70	2.79	0.22	14.31	60	1.13	1.04	0.15	5.11
Labor (million ¢)	58	1.72	1.78	0.14	9.15	60	1.39	1.28	0.19	6.30
Other Inputs (million ¢)	58	5.83	6.03	0.48	30.94	60	5.76	5.33	0.78	26.12
Return to water (million ¢)	58	14.16	14.65	1.17	75.11	60	14.85	13.73	2.00	67.31

The contribution of capital, labor and other non-water inputs to the total revenue were 11%, 7% and 24% for Tono and 5%, 6% and 25% for Dorongo (Figure 5.5). Increased contribution of capital at Tono shows that capital was more important for tomato farmers there than at Dorongo. The rather small contribution of labor at both sites does not necessarily imply that labor was not an important input in tomato farming but rather, that labor was highly underpaid at the study sites. The average labor charge was about one dollar per laborer per day and less than the official minimum wage rate for Ghana, which was about ¢11,000 (1.22US$) during the study period. The contribution of farming inputs to the total production was almost the same at the study sites, and was 24% at Tono and 25% at Dorongo. Economic returns to water in Tono and Dorongo were also similar but with a slightly increased spread at Tono compared to Dorongo.

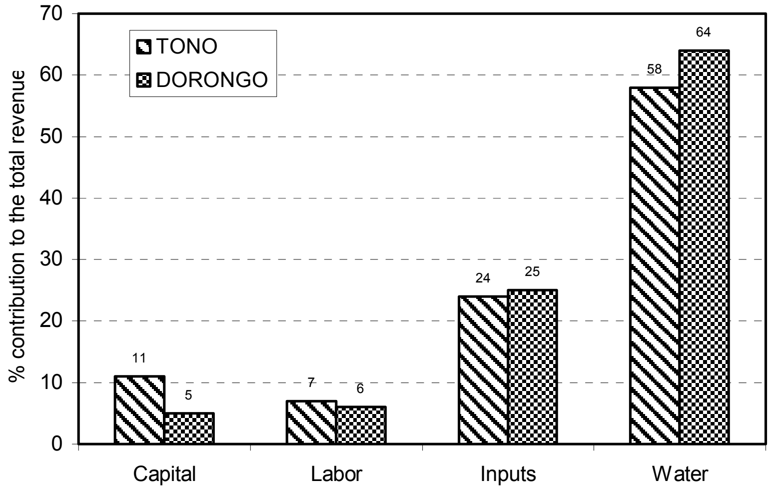

Figure 5.5: Percentage contribution of production factors to total revenue

5.3.4 Estimated value of irrigation water

The economic return to water was about 58% and 64% of the mean total revenue at Tono and Dorongo, respectively (Table 5.10). Assuming a minimal influence of market irregularities on goods and services during farming operations in this study and that costs were representative of local markets, high economic returns to water show the importance of water for dry season tomato farming. By considering consumptive transpiration as the only water flow in an agricultural field passing through the crop (Bouman, 2007), theoretically leads into higher estimates of the value of water (3442.69 ¢/m^3 or 0.38 US$/m^3 and 4352.95 ¢/m^3 or 0.48 US$/m^3) at both study sites. Although the value of water based on consumptive transpiration would have beeen economically favorable, the underlying assumption, that water supplied to crop plants will only meet transpiration is technically not feasible under most current surface irrigation schemes.

Apart from groundwater percolation, evaporation from soil surfaces constitutes a part of irrigation water requirements. The estimated value of water based on consumptive ET is in general a primary target required to be attained by water management strategies under plot, farm and irrigation scheme scales. The values of water based on ET_a and ET_c were slightly higher at Dorongo than at Tono because of lower returns to water but also due to the elongated growth period and higher water use at Tono than at Dorongo.

Table 5.10: Estimated value of water for tomato irrigation

Item	Tono		Dorongo	
	¢/ha	US$/ha	¢/ha	US$/ha
Total revenue	24,413,549	2704	23,126,008	2561
Cost of non-water inputs	10,253,777	1136	8,278,085	917
Economic return to water	14,159,771	1568	14,847,923	1644
*Average value of irrigation water per:	¢/m^3	US$/$m^3$	¢/m^3	US$/$m^3$
T	3442.69	0.38	4352.95	0.48
ET_a	2885.33	0.32	3127.85	0.35
ET_c	2730.91	0.30	3076.01	0.34
I	1796.93	0.20	2779.21	0.31

*T, ET_a, and ET_c are average values determined in Chapter 4. The exchange rate used is 1US$ =9030 ¢.

The estimated value of water based on irrigation deliveries represents the value of total inflow measured at the inlet of the plot. It includes actual crop water consumption and deep percolation losses to the ground, which are both regarded as depletive at plot scale. Because of the increasing denominator of irrigation deliveries, estimated values based on irrigation deliveries were the lowest (1796.9 ¢/m^3 or 0.20 US$/$m^3$, and 2779.21 ¢/$m^3$ or 0.31 US$/$m^3$) among the indicators used, both at Tono and Dorongo.

In this study, irrigation deliveries are considered a good indicator of the estimated value of water at Dorongo, since part of the deliveries lost to groundwater percolation cannot be reused within and downstream of the scheme, because no downstream flows exist during most periods of the dry season farming. Although such percolation could be contributing to the main groundwater body that supplies, among other uses, domestic water in traditional and pumped boreholes, it is a lost resource from the individual farmer's point of view. However, at Tono, the value of water based on actual evapotranspiration could be a good indicator because of potential reuse of surface and deep percolation losses occurring at field and farm levels. Apart from reuse, surface and deep percolation losses occurring at field and farm levels. Apart from reuse, the drains also contribute to in-stream flows maintaining the river ecosystem functions. Based on the T-test for the differences of the means, estimated values of water for all indicators at Tono and Dorongo were not significantly different at the 5% significance level. However, the values were significantly different at the 5% significance level within the schemes, with decreasing values from average consumptive transpiration to irrigation deliveries.

The value of irrigation water in this study is relatively higher than commonly reported values of water from related environmental conditions (Ariel et al., 2000). FAO (2005) reported a range of 0.14-0.18 US$/m^3 for tomato irrigation in the southern highlands in semi-arid in Tanzania. General values of 0.2 US$/m^3 and 0.4 US$/m^3 for tomatoes under surface and drip irrigation, relatively closer to present study values, were reported for semi-arid Mediterranean region (Laquet et al. 2004). The value of water under the present study is far higher than the values for crops with higher water requirements such as rice. However, methodological differences from which the values are derived seriously limit any meaningful comparison between water valuation studies.

5.3.5 Summary and conclusions

- Farm plot sizes in dry season irrigation of tomatoes in the UER are generally small. The mean plot size allocated per farming household during the 2005/06 dry season were 0.7 ha and 0.2 ha at Tono and Dorongo, respectively. More than 70% of the farmers were allocated plots varying from 0.4 ha to 1.4 ha at Tono and above 60% at Dorongo were allocated plots ranging from 0.09 ha to 0.28 ha.

- The majority of farmers in the study area lack sufficient capital for dry season irrigated tomato farming. Access to capital is important because of the capital-intensive, high-input and labor-intensive dry season tomato farming. With the exception of fuel and fertilizer use, farm input at the two sites was not different. Increased use of fuel and fertilizers at Dorongo could be associated mainly with increased distance of pumping and the difficulty in estimating accurate quantities of inputs for extremely smaller plots. The costs for seeds, fertilizers, pesticides and fuel were slightly higher at Dorongo than at Tono.

- The mean total labor use at the two study sites was similar. However, the mean total labor cost at Dorongo was 17 % less than at Tono because of the reduced labor cost for harvesting at Dorongo. The use and cost of labor for combined irrigating and harvesting was about 50% of the total labor use and labor cost at the two sites.

- Economic returns to water at both sites were above 50% of the total production, indicating the importance of irrigation water for dry season tomato farming. The value of water showed a decreasing trend from consumptive transpiration to irrigation deliveries. Although the mean values of water within sites for the different indicators were different, they were not significantly different between the sites at 5% significance level. Since return to water at Tono was slightly lower than at Dorongo, improvement in water use efficiency through improved water management might have a more positive influence on the value of water at Tono compared to Dorongo.

6 ADDED VALUES TO RESERVOIR WATER FROM LIVESTOCK WATERING AND FISHERY

6.1 Introduction

6.1.1 Livestock

Livestock contributes about 7% of Ghana's agricultural gross domestic product (GDP) (FAO, 2006 and 1996). In the UER, livestock form an integral part of crop-livestock farming systems. The total number of livestock for the region between 1992 and 1996 was about 18%, 8%, 3% and 7% of the national population of cattle, sheep and goats, pigs and poultry, respectively (Karbo and Agyare, 1998). Regionally, livestock form an important sector on which development of land and water resources focuses.

The assessment of livestock water-productivity or value of water for livestock uses, defined as the ratio of livestock products and services to the depleted water (Peden et al., 2003), is fraught with uncertainties due to interconnectedness between livestock inputs and outputs (products and services) and the agro-ecosystems that support them. Livestock products and services may include meat, milk, carcases, skins and hides, manure, and animal power, while depleted water as the main input can be viewed in terms of both physical and quality depletion. Quantity depletion occurs through evapotranspiration associated with livestock feeds and fodder, and quality depletion includes water pollution due to contamination with animal urine and feces, which render water unfit for other uses. Other impacts of livestock keeping on water resources include soil erosion aggravation and sedimentation, and habitat destruction (McCornick et al., 2002). Generally, the direct water intake or drinking water is of minor significance in terms of livestock water budgets in farming systems, since the water needed to produce livestock feeds can be up to 100 times more than the animals' direct water consumption per day (Peden et al., 2003). Livestock drinking water may constitute less than 2% of the total amount of water used for livestock production. However, drinking water contributes significantly in livestock production, especially in hot semi-arid areas, where the water contents in livestock feeds, particularly grasses, may drop below 20% during the dry season. Drinking water contributes about 70% of the livestock body weight, and its deficiency directly affects metabolic activities and leads to reduced feed intake, production and reproduction, and to poor health and death

(Peden et al., 2003; King, 1983). Further, most domesticated animals can survive about 60 days without feed but less than 7 days without water (Molden, 2007).

It is possible to assess livestock-water productivity by considering all products and services in addition to direct water inputs using water accounting tools, which depict the various paths of water input under a defined system in time and space (Molden, et al., 2003). Such approaches, although sound in principle, face practical challenges at local scale in semi-arid areas and the UER, in particular due to constraints arising from the following: (i) Free range management is commonly practiced during the dry season with the majority of livestock types such as cattle, sheep, goats and donkeys, utilizing crop residues and grasses grown under rain-fed conditions; (ii) dry season crop residues from irrigation schemes are a minor component of livestock feed requirements, and the residues are generally completely grazed in the fields one or two days after crop harvesting; (iii) the majority of livestock types in the UER are not kept entirely for livestock products and services, but also serve as assets and insurance against risks of, e.g., crop failure from drought, and are sold or slaughtered only when a need arises, making capture of the full range of outputs unpractical for livestock-water productivity assessment as suggested; (iv) some livestock products such as cow dung have a multitude of uses including use as manure, plastering for walls of dwelling houses, traps for termites and ants used as poultry feeds, and household fuels (Karbo and Agyare, 1998), which complicates the traceability of the value for such livestock products. Rao et al. (2005) reported that only one-third of the crop residues, mainly from groundnuts and legumes, are available as livestock feed in the West African sub-region, while two-thirds are used for other purposes.

Livestock-water productivity assessments based on water accounting are practical when livestock feeds are produced from a well defined water system that facilitates the partitioning of water flow into feeds and fodder, and where inputs and outputs can be identified and quantified. However, for planning of reservoir water resources development, the main source of livestock water supply in the UER, quantity of drinking water may be a reasonable basis for estimating the value of water for livestock watering.

In this study livestock farming is assumed a low input production activity, involving water consumed in the production of livestock feed, veterinary services and labor as the main inputs. The feeds consist mainly of grasses and shrubs (vegetation), which grow naturally during the rain season and are not managed. The average market prices for live animals are used to estimate the current value of reservoir water for livestock watering.

6.1.2 Fishery

Fisheries contribute about 5% to Ghana's Agricultural GDP (Neiland and Béné, 2003), and fish is the main source of meat protein in urban and rural areas, and is especially important in poor rural communities unable to afford other sources of meat protein. The annual per capital fish consumption is above 20 kg, which is about 60% of the animal protein intake (Seini, et al., 2002). Inland fisheries contribute about 20% of the total fish production in Ghana. Of this, the Volta Lake alone contributes about 80%, while the remaining fish come from rivers and reservoirs. Although no records on fish output are available from small reservoirs and rivers in the UER, fishery is an important emerging sector, and fishery policies are relevant in fighting poverty by utilizing existing reservoir water resources.

Fisheries are conceptually non-consumptive users of water, although water requirements to maintain fisheries have been estimated under different fishery cultures. In exclusive fishery farming systems such as fish ponds, water requirements to produce a given yield have been defined in terms of water used in feed production, fish pond drainage and water loss (Brummett, 2005). Pond drainage and water losses are counted as consumptive requirements especially when these outflows cannot be further recycled. For example, Palanisami et al. (2006) used pond dead storage and water loss to estimate the value of water for fishery farming in India. Monthly reservoir storages were also used to estimate the value of water for fisheries in the Kirindi Oya Irrigation System Project (KOISP) in Sri Lanka (Renwick, 2001).

In farming systems not specifically designed for fisheries, such as integrated rice-fish aquaculture and irrigation reservoirs, fisheries can be considered an added benefit to existing production systems. Integrating fisheries in such farming systems generally does not require additional water (Dugan, et al., 2004). In this study, the dead storage volumes[1] of the reservoirs are used as data in the assessment of the value of reservoir water for fisheries. The volume of water maintained in the dead storage is important for sustaining fisheries until the next rain season when the reservoirs are filled with rainfall runoff. The dead storage volume appears to be an important indicator for determining the value of water given the fact that currently fishes are not stocked annually in the study reservoirs, ruling out the possibility of survival of existing fish stocks in the event of dead storage volume depletion. Fisheries in secondary storages along the main canals, main river channel, irrigation canals and drainage channels at Tono are not included due to absence of fishery records.

6.2 Methodology

6.2.1 Livestock

Livestock population data for the study areas were collected from Navrongo and Bolgatanga MOFA District Offices. At Navrongo, the livestock populations are based on the 2003 population projections developed using the 1999 district livestock census, while at Dorongo the populations are based on 2005 livestock head count in the community conducted by the Bolgatanga MOFA District Office. The livestock population include cattle, goat, sheep, donkeys, pigs, local poultry, dogs and rabbits. Using these livestock records, the populations of livestock depending on reservoir water for drinking at Tono were estimated to about 38% for cattle and sheep, 81% for goats and 19% for donkeys of the total district livestock population. Local poultry (chickens, fowls, and ducks), pigs and rabbits were not included in the assessment, since majority of these animals depend on domestic water supply from community boreholes.

The value of water for livestock is estimated using two livestock market prices: 1) national average livestock producer price of US$ 511/ton of live animal weight (FAOSTAT database), and 2) local average market price of US$219/ Tropical Livestock Unit (TLU) collected during the study period. The following assumptions are defined and applied to estimate the value of water:

1. All the livestock in the study area are converted to the equivalent TLU, and one TLU is equivalent to 250 kg (Peden et al., 2003).

[1] Storage in reservoirs held below intake points

2. Livestock depend mainly on pasture for feeds, and only 25% of the total feed consumption comes from rainfed and irrigated crop residues.
3. The live weight of 250 kg per TLU is attained within three years of animal growth. The body weight gain of local West African cattle breeds, for example, can be above 70 kg in 200 days (Jutzi et al., 1988).
4. The livestock during the study are about 5 years old. Beef cattle are generally slaughtered at an age of about 2 to 3 years (Champagain and Hoekstra, 2003; Jutzi et al., 1988), however in semi-arid SSA cattle can survive up to 10 years, particularly calving and oxen animals. The amount of water used to produce feeds is based on the daily TLU dry matter intake of 5 kg/TLU minus 25% of the total dry matter contributed from crop residues. About 250 l of water is depleted for every kg of dry matter produced (Molden, 2007).
5. About 10% of the total market value of TLU is incurred for veterinary and other livestock service costs, while 1% of the total TLU market value is incurred for the grazing labor cost.
6. During the rainy season, the moisture content in livestock feed can go up to 70% (King, 1983), and direct water consumption is taken as 50% of the amount consumed directly during the dry season.

The total amount of water depleted for producing livestock feed at each study site can be estimated as (Eq. 6.1):

$$LFWD = NTLU \times DMR \times ND \times UDET \qquad (6.1)$$

Where: LFWD is the livestock feed water depletion [m^3], NTLU is the total number of livestock units [-], DMR is the dry matter requirement per TLU per day [$kg day^{-1}$], ND is the number of days [-] , and UDET is the unit dry matter evapotranspiration [$250\ l\ kg^{-1}$].

Daily drinking water intake (m^3/TLU) for the different types of livestock under dry and hot tropical environments (Peden, et al., 2003) was used to estimate water consumption of total TLU per season (Table 6.1).

Table 6.1: Livestock types, total tropical livestock units (TLU) and water consumption

Livestock type	Unit TLU*	Daily water intake (l/TLU/day)*	Tono		Dorongo	
			Livestock no.	Total TLU	Livestock no.	Total TLU
Cattle	0.7	38.6	19469	13629	560	392
Sheep	0.1	50.0	11952	1195	720	72
Goats	0.1	50.0	25995	2600	650	65
Donkeys	0.4	40.0	287	115	155	62
Total			57703	17538	2085	591

* Peden et al. (2003).

The total value of water was estimated as a ratio of the net return from total TLU to total water consumed. The yearly average value was obtained by dividing total value by the age of the livestock (5 years).

6.2.2 Fishery

Labor, fishing canoes and nets (gill nets) are the main inputs used in fishery activities. It was assumed that 75% of the canoes and total number of fishermen (180) were engaged on fishing expeditions every day during the dry season at the Tono reservoir. Fishermen spend about 4 hours per day on average for fishing activities, which is valued as equivalent to 50% of the daily wage rate of ¢10,000. Total labor cost for all participating fishermen was estimated as the product of price of daily labor input per fishermen, total number of fishermen and total number of fishing days (212, from October to April). The cost of fishing nets was estimated as the product of the average unit price of a 12.7 cm fishnet (¢140,000) and the total number of fishnets used per season (146). Fishing canoes have been used for the last 15 years and therefore were excluded in the valuation under this seasonal analysis. At the Dorongo reservoir, the labor cost was estimated using a labor value of ¢2,500 per fishermen for a 2-hour fishing expeditions per day for a total number of 12 fishermen engaged in 30 days of fishing activities per season. Although other fishing gears such as fishhooks and scooping are used in addition to fishnets, for simplicity it was assumed that three small-sized fishnets with a unit price of ¢50,000 are required to support all the fishermen per season at Dorongo.

Data on the monthly catch of fish at Tono reservoir were collected from the fishery department at Navrongo MOFA district office and ICOUR monitoring office

(Figure 6.1), and seasonal fish yield was estimated from the collected monthly fish catches.

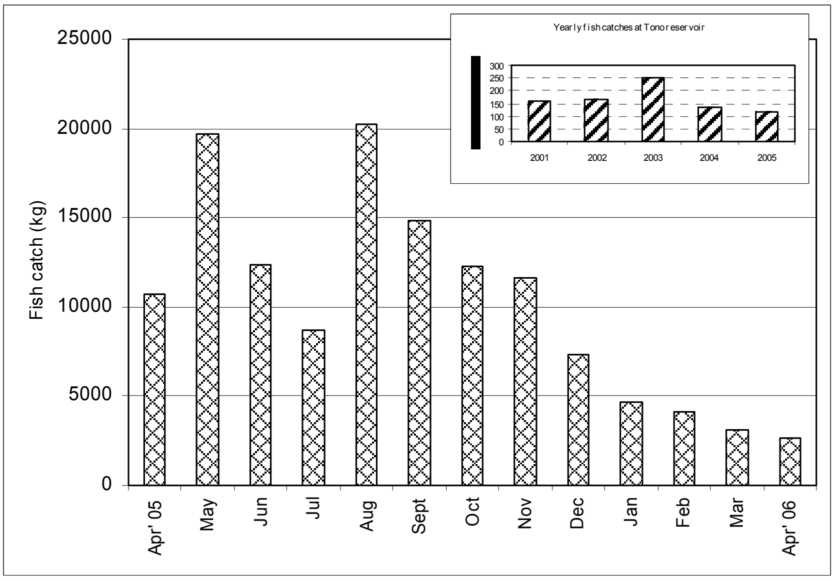

Figure 6.1 Monthly and annual fish yield at Tono reservoir

At Dorongo, the total fish yield was estimated by monitoring fish catches during fishing events in the field. At both sites, the average price of fresh fish per kilogram during the dry season as collected from the Navrongo market was used to estimate gross revenue from the fish yield. Net revenue was estimated by subtracting the total cost of labor and fishing nets from the gross revenue. The value of water was estimated as the ratio of net revenue to the dead storage volume of the reservoir. The design dead storage volume at Tono was adjusted to current dead storage volume using the 1996 reservoir sedimentation estimate rates (ICOUR, 1996). At Dorongo, the dead storage volume was estimated from field bathymetric measurements (surface area and depth) of dead stored water.

6.3 Results and discussion

6.3.1 Livestock

Estimated livestock drinking water was about 4% of the total livestock water consumption (Table 6.2). The value of water for the total depleted water ranged from 851 to 1333 ¢/m^3 (0.09-0.15U S\$/m^3). The contribution of the seasonal livestock drinking water to seasonal total value of water varied from 15 to 23 ¢/m^3. It is generally difficult to obtain a precise estimate of the value of water for direct consumption even when estimates are based on livestock products and services. This is because part of the water directly consumed, with the exception of the water lost by body evaporation for cooling and in urine and feces, is maintained in the animal body system for metabolic processes and contribution to the animal's body weight turnover (King, 1983).

Table 6.2: Value of water for livestock

Variable	National average producer price		Average local market price	
	Tono	Dorongo	Tono	Dorongo
Returns from livestock (x 10^6 ¢)	19940.34	671.95	31217.76	1051.98
Water depleted by livestock feed (x $10^6 m^3$)	22.50	0.76	22.50	0.76
Drinking water (x $10^6 m^3$)	0.92	0.03	0.92	0.03
Total water consumption (x $10^6 m^3$)	23.42	0.79	23.42	0.79
Livestock water productivity (¢/m^3)	851		1333	
Average annual value of water for livestock (¢/m^3)	170		267	
Seasonal value of water for livestock (¢/m^3)	85		133	
Drinking water contribution to seasonal value (¢/m^3)	15		23	

The revenue from the animal sale is generally considered an extra benefit when the estimate of the value of water is based on livestock products and services. Using feed and fodders as the main livestock inputs and draft power, transport power, threshing power, manure, and product sales (e.g., milk and manure) as services and products, Peden et al. (2005) obtained values between 0.143 and 0.489 US$/$m^3$ for livestock for small-scale irrigation schemes in the Upper Awash River Basin of Ethiopia. Estimated total value of water for livestock in the current study is lower than estimates by Peden et al. (2005), mainly due to the differences in approach and data used. Out of the many products and services that are required for livestock-water productivity analysis, only the water input and current market of the livestock were available in this study. However, from the few available studies on the value of water for livestock, no clear trend can be observed between the values determined based on single components and those based on complete set of livestock products and services (Planisami et al., 2006, Singh and Kishore, 2004, Peden et al., 2005, Chapagain and Hoekstra, 2003).

Using the definition of livestock-water productivity as the ratio of milk net profit to water used (m^3), Palanisami et al. (2006) obtained between 0.24 and 0.67 US$/$m^3$ as the economic value of water for dairy livestock at Tamil Nadu in India. Lower estimates equivalent to the contribution of drinking water to seasonal value in this study have been reported. Singh and Kishore (2004) estimated a value of 0.004 US$/$m^3$ for the water-intensive indoor dairy cattle in western India. As indicated by the authors, the low values were the result of high water input in the production process. Livestock production using water-intensive feed and fodders generally results in low water productivity. The integration of crop and livestock into the crop-livestock production system, where livestock depend on crop residues for their feed, is potentially a relevant strategy for improving livestock-water productivity in rainfed and irrigation systems (Molden, 2007). The integrated crop-livestock production system require less water, since the water used to produce crop residues is normally counted for in the crop WP (e.g., grains). However, for sustainable integrated crop-livestock production systems, maintaining a small-livestock herd may be necessary, an innovation that the majority of traditional livestock keepers may find difficult to adopt.

Although the results obtained in this study might not be generally comparable due to data limitation, a decisive factor in the methodological approach, they do provide an indication of the possible value of reservoir water for livestock drinking in the UER. The results also provide important information useful for seasonal planning of reservoir water resources management under multiple water uses and show how important livestock water allocation is, given competing uses.

6.3.2 Fishery

Labor constituted the largest component of fishery production costs, i.e., 88% at Tono and 86% at Dorongo, while fishnet costs contributed only 12% and 14%, respectively (Table 6.3). Although the net return to water for Tono was higher than for Dorongo, the value of water at Tono was only 50% of the value of water at Dorongo, due to increased volume of dead storage maintained at the end of the dry season.

Table 6.3: Fishery production and value of water for fishery at Tono and Dorongo

Variable	Tono	Dorongo
Total labor cost per season (x 10^6 ¢)	143.1	0.9
Total cost of nets per season (x 10^6 ¢)	20.44	0.15
Total production costs (x 10^6 ¢)	163.54	1.05
Total fish yield per season (kg)	45,960	120
Average seasonal price of fish (¢/kg)	22,405	22,405
Gross revenue (x 10^6 ¢)	1029.71	2.69
Net returns (x 10^6 ¢)	866.17	1.64
Value of water for fishery		
Dead storage volume (m^3)	8,790,954	8,203
Value of water (¢/m^3)	98.53	199.76

Values of water for fisheries vary widely depending on the fishery production system. For example, using a combination of dead water storage and evaporated volumes of water, Palanisami et al. (2006) obtained a range from 1.42 to 1.67 US$/$m^3$ for a pond fishery system in India. Lower values ranging from 0.002 to 0.034 US$/$m^3$ were reported by Renwick (2001) for KOISP in Sri Lanka. Although methodological differences exist in the assessment of the value of water for fisheries, some of the studies indicate decreasing unit values with increasing size of reservoirs in the tropics due to reduced surface-area volume ratios in large reservoirs, resulting in lower primary production (Jackson and Marmulla, 2001). Such a disparity in unit values may also reflect improved management aspects in small reservoirs, although it could also be as a result of many other factors such as increased stocking rates, type of fish species, and fishery management system (Brummett, 2005). However, when such differences are contextualized in terms of improvement in social welfare reflected by the number of people employed by fisheries in reservoirs with large surface areas such as the Volta Lake, fisheries in large water bodies (reservoirs and lakes) might be more beneficial than in small water bodies.

6.4 Summary and conclusions

The added values for every cubic meter of reservoir water ranged from ¢15 to ¢23 (0.002-0.003 US$) at Tono and Dorongo for livestock watering, and ¢99 (0.01 US$) and ¢200 (0.02 US$) for fishery at Tono and Dorongo, respectively. Including livestock products and services would provide a more reliable estimate of the value of water for livestock in the study area. However, it may be very difficult to obtain sufficient and reliable data on livestock products and services given the nature of livestock farming in the area, which is not entirely livestock-products oriented but asset oriented. Large dead storage volume at Tono resulted in a reduced value of water for fishery compared to Dorongo. The added values to reservoir water from livestock and fishery water uses were lower than the estimated value of water for tomato irrigation. It is important to note that the results obtained show approximate current values of water for livestock and fisheries, and better estimates may be obtained when all relevant data become available and used future studies.

7 FACTORS CONTRIBUTING TO THE VALUE OF WATER FOR TOMATO IRRIGATION

7.1 Introduction

The value of water for crop production can be influenced by many factors such as crop physiology, land and water management, agronomic practices and farming inputs. Crop physiological attributes, e.g., plant type, crop tolerance to drought, diseases and heat, and adaptation to different environmental conditions, which are important for improving the value of water, are generally developed using crop biotechnology and crop breeding techniques (Oweis and Hachum, 2003; Bouman, 2007). With the exception of environmental conditions, the physiolocial attributes can be influenced for example, via the introduction of irrigation. Engineering techniques are also used for developing land and water management practices important to improving the value of water (Bouman, 2007). Both crop biotechnology and engineering techniques require long-term to develop viable technologies.

Considering that water is the most important factor in determining crop yield, which in turn influences the value of water, water-yield relationships (functions) are often used for estimating the amount of water required to attain optimum or maximum crop yield for a given crop in a particular season or the yield corresponding to a given level of water input. The water-crop yield relationships are based on physical measurements of yield under known varying volumes of water or irrigation application. The water-crop yield relationships developed by Doorenbos and Kassam (1979) have wide application in studying water-yield functions under different agro-ecological zones (Norwood, 1997; Al-Jammal et al., 2000; Kiplorir et al., 2001). Factors such as water and salinity stress, which affect crop yield directly, and water productivity indirectly can be incorporated in most of the water-crop yield functions (Prendergast, 1993; Allen et al., 1998).

However, when the contribution of other variables such as fertilizer use, crop acreage and crop timing to crop yield have to be determined in addition to the influence of water, then water demand functions, production functions, or regression models are preferred over the single input-output water-yield response functions. For example, fixed allocatable input, variable input and behavioral water demand models were applied to assess on-farm water productivity of wheat in dry regions of West Asia and North Africa (UN, 2003). In these models, irrigated area, output price, labor wage rate, farm available water, irrigation technology, and water limitation were the main explanatory variables. Most of the variables required in the production functions and regression models can easily be collected in farm surveys, although the confidence in resulting analysis is often highly uncertain. However, the requirement of the volume of water applied per farm as an input in the production functions is often an obstacle, because data on water supply per farm, per plot or per sub-unit of irrigation systems may not be available particularly in developing countries to facilitate reasonable estimates of the production functions. Hussain et al. (2004) used 218 measurements of farm water supply to identify factors contributing to the water productivity for cotton and wheat in the Upper Indus Basin of Pakistan. Irrigation water supply for each of the 218 farms was measured using V-notch weirs. To achieve such a large number of water measurements, sufficient time resources are required. Remote sensing techniques are becoming increasingly useful in reducing data collection burdens. This particularly applies to biophysical crop parameters which can be easily integrated with available field water supply records (Bastiaanssen et al., 2003).

Using water productivity as a dependent variable, Oweis and Hachum (2003) obtained a curvilinear relationship between crop water productivity and crop grain yield for durum wheat under supplemental irrigation in Syria. Similar relationships were also obtained for wheat under different crop water use in the Indus Basin in Pakistan (Bastiaanssen et al., 2003). The single input-output form of relationship can be extended to assess the contribution of other production factors in a production function. In such extended production functions, the value of water takes the position of the dependent variable instead of crop yield. The extended form of relationship between the value of water and its contributing factors is applied in this study to gain an understanding of the factors contributing to the value of water for dry season irrigated tomatoes farming at the Tono and Dorongo schemes.

7.2 Methodology

A multiple linear regression (Eq. 7.1) was applied to assess the contribution of other variables to the value of irrigation water using field survey data described in Chapter 5.

$$VW = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_n X_n + \varepsilon \qquad (7.1)$$

Where: VW is the value of water (¢/m^3), β_0 is a constant, and $\beta_1 .... \beta_n$ are coefficients of the regression equation, $X_1 ..... X_n$ are the explanatory variables (Table 7.1) and ε, is the deviation between the observed and predicted values.

The errors are assumed to be independent and normally distributed with zero mean and standard deviation, σ.

Table 7.1: Explanatory variables specified in the regression analysis of the factors contributing to the value of water

Variable	Definition	Variable	Definition
X_1	Scheme (1=Tono, 0 = Dorongo)	X_8	Number of fertilizer applications (1= twice; 0 otherwise)
X_2	Size of plot (ha)	X_9	NPK fertilizer use (kg/ha)
X_3	Tomato variety (1= Petomech VF, 0 otherwise)	X_{10}	Pesticides use (kg/ha or l/ha)
X_4	Crop growth season (days)	X_{11}	Plowing method (1=Tractor, 0 otherwise)
X_5	Irrigation method (1=surface canal, 0 otherwise)	X_{12}	Total labor use (mandays)
X_6	Total yield (kg/ha)	X_{13}	Price of fresh tomatoes (¢/kg)
X_7	Tomato seed use (kg/ha)		

Dummy variables were defined for scheme, crop variety planted, irrigation method, number of fertilizer applications and method of plowing. The variable scheme captures differences in location characteristics such as soil properties while the variety indicator is intended to capture the contribution attributable to variety differences within and between schemes. For the variable variety, a dummy value of one was used for Petomech VF, which was planted by the majority of farmers at both study sites, and a value of zero was used for the other varieties. Dummy variables for the number of fertilizer applications and plowing methods are intended to capture the contribution from the number of fertilizer applications and the methods of land preparation, respectively, to the value of water.

The regression coefficients and regression models were tested during the analysis. Scatter plots of dependent and independent variables were used to check for the linearity of the variables (independent observations). The normality of the distribution of the residuals and variance homogeneity of residuals were tested using normal and cumulative probability plots of the residuals. Autocorrelation and multicollinearity of the independent variables were tested using the Durbin Watson test, tolerance factors (TF), and the variance inflation factors (VIF), while Cook's and leverage statistics were applied to test the influence of outliers. The F-test and T-test were used for the significance test of the regression equation and coefficients.

7.3 Results and discussion

The estimated regression models are different specifications of the dependent variable, value of water (VW). The dependent variables are the imputed values of water based on transpiration (VW_T), actual and potential crop evapotranspiration (VW_{ETa} & VW_{ETc}), and irrigation water supply (VW_I) for the first (Reg1), second (Reg2), third (Reg3), and fourth (Reg4) regression models, respectively. In all the estimated regression models, only the variables scheme (X_1), crop yield (X_6) and price (X_{13}) contributed significantly (1% probability) to variations in the different indicators of the value of water (Table 7.2). Scheme location contributed negatively to the value of water, with more reducing effects for Reg1 and Reg4 than in Reg2 and Reg3. The fact that the value of water at the two study sites could be influenced by site specific factors such as soils, water management, pests and diseases, it is difficult to single out the reason for the lower value of water at Tono, though poor crop yield due to crop pests and disease infestation were cited in the previous chapters among the reasons for the water productivity differences. Crop yield as expected contributed positively to the value of water in all regression models because of the direct relationship between yield and the value of water. The regression coefficients for crop yield suggested a systematic pattern, being large in the Reg1 followed by Reg2, Reg3 and Reg4 models, which reflects the different versions of the dependent variables specified. Assuming a constant price of harvested crop yield, such a pattern portrays the changing magnitude of the value of water based on different indicators of crop water use. For every increase in crop yield, there is a stronger influence on the value of water under crop transipiration than that under irrigation water supply because of the direct contribution of transpiration to crop yield while part of the irrigation supply for example may get lost in the distribution system and on the farm. Linear and quadratic relationships between water productivity and crop yield have been reported under single input-output (Bastiaanssen et al., 2003; Rockström et al., 2003; Oweis and Hachum, 2003). Also, Bastiaanssen et al. (2003) indicated that water productivity was more influenced by wheat crop yield than by water input in the Indus Basin. Although a multi input-single output analysis is applied in the current study, crop yield and price (X_6 and X_{13}) appears to have more effect than other variables. However, the price of the crop (X_{13}) which is a part of the definition of water productivity, is considered as an important unit in the determining the value of water and cannot be be treated in the same way as the other explanatory variables. The regression coefficients for crop price show a pattern similar to the crop yield coefficients.

The coefficients of the remaining variables were not significantly different from 0 at the chosen level of significance, although they contribute to the overall significance of the estimated regressions models. Plot size (X_2) was positively associated with the value of water. In water scarce regions, the area under irrigation could be one of the factors determining the value of water if deficit irrigation is practiced and additional land is put under crop as long as net benefits would be the same or more than when crops are supplied with full irrigation (Oweis and Hachum, 2003; Rockström et al., 2003; Zhang, 2003). The slightly larger coefficient on the size of plot variable (X_2) in Reg1 as compared to the other models could suggest that, by supplying only the amount of water required for transpiration (assuming other losses are avoided), a larger area could be irrigated, thus increasing the value of water tremendously given the available water resources. However, in multiple linear regressions other variables need to be examined in order to determine the significance of the coefficients in relation to the value of water.

Table 7.2: Regression coefficients of the factors contributing to the value of water

Variable	Dependent variable-VW_T (Reg1)				Dependent variable-VW_{ETa} (Reg2)				Dependent variable-VW_{ETc} (Reg3)				Dependent variable-VW_{IRG} (Reg4)			
	Coefficient	Std. Error	t	Prob > |T|	Coefficient	Std. Error	t	Prob > |T|	Coefficient	Std. Error	t	Prob > |T|	Coefficient	Std. Error	t	Prob > |T|
Constant	-3824.13	1043.85	-3.66	0.0004	-2885.85	613.18	-4.71	0.0000	-2802.28	635.19	-4.41	0.0000	-2323.03	839.50	-2.77	0.0067
X_1	-962.04	246.91	-3.90	0.0002	-379.25	145.04	-2.61	0.0103	453.79	150.24	-3.02	0.0032	-939.68	198.57	-4.73	0.0000
X_2	173.47	167.59	1.04	0.3030	112.96	98.44	1.15	0.2538	114.12	101.98	1.12	0.2657	123.76	134.78	0.92	0.3606
X_3	-15.11	183.38	-0.08	0.9345	-20.43	107.72	-0.19	0.8500	-17.61	111.59	-0.16	0.8749	0.06	147.48	0.00	0.9997
X_4	6.12	5.56	1.10	0.2738	2.82	3.26	0.86	0.3902	3.18	3.38	0.94	0.3494	5.56	4.47	1.24	0.2166
X_5	-49.72	143.52	-0.35	0.7297	-54.63	84.31	-0.65	0.5184	-48.83	87.33	-0.56	0.5773	-12.67	115.42	-0.11	0.9128
X_6	0.25	0.01	39.66	0.0000	0.20	0.00	54.11	0.0000	0.19	0.00	49.97	0.0000	0.14	0.01	27.59	0.0000
X_7	-94.63	1890.86	-0.05	0.9602	67.44	1110.74	0.06	0.9517	31.24	1150.61	0.03	0.9784	-199.75	1520.70	-0.13	0.8957
X_8	-100.15	343.71	-0.29	0.7713	-26.06	201.90	-0.13	0.8975	-37.52	209.15	-0.18	0.8580	-111.56	276.42	-0.40	0.6873
X_9	0.29	0.72	0.41	0.6842	0.29	0.42	0.69	0.4903	0.27	0.44	0.61	0.5439	0.10	0.58	0.18	0.8559
X_{10}	48.16	40.74	1.18	0.2398	29.20	23.93	1.22	0.2252	30.11	24.79	1.21	0.2272	36.58	32.76	1.12	0.2668
X_{11}	-260.68	212.95	-1.22	0.2237	-98.98	125.09	-0.79	0.4306	120.22	129.58	-0.93	0.3557	-258.49	171.26	-1.51	0.1343
X_{12}	-2.62	7.89	-0.33	0.7405	-2.52	4.64	-0.54	0.5877	-2.31	4.80	-0.48	0.6309	-1.03	6.35	-0.16	0.8708
X_{13}	2.45	0.10	25.17	0.0000	1.76	0.06	30.78	0.0000	1.73	0.06	29.23	0.0000	1.58	0.08	20.18	0.0000
N	118				118				118				118			
R	0.981				0.989				0.987				0.966			
R^2	0.963				0.978				0.975				0.966			
F-Test	$F(13, 104) = 206.27$; Prob.>F = 0.000				$F(13, 104) = 357.71$; Prob.>F = 0.000				$F(13, 104) = 309.92$; Prob.>F = 0.000				$F(13, 104) = 113.34$; Prob.>F = 0.000			

Variety use (X_3) suggests mixed results, i.e., a negative association for Reg1, Reg2 and Reg3 and a positive association for Reg4. While variety preference could be influenced by increased yield, resistance to pests and diseases, and quality of harvested tomatoes, the change in sign for the variety coefficient in Reg4 is probably due the difficulty in isolating the variety effects from other contributing variables given the low value of water under irrigation supply. This is because variety is one element among the bunch of agronomic practices that also contribute to the value of water (Oweis and Hachum, 2003). Length of crop growth (X_4), quantity of fertilizer (X_9) and pesticides (X_{10}) associate positively to the value of water. The rate of association to the value of water for every increase in crop season differs among the regression models, being almost twice for Reg1 and Reg4 compared to Reg2 and Reg3. Fertilizer use (X_9) suggests almost constant effects among the regressions except for Reg4. Pesticides use (X_{10}) suggests more positive association to the dependent variable for Reg1 and Reg4 than for Reg2 and Reg3. Although fertilizer and pesticide application contribute insignificantly to the value of water, use of fertilizers definitely contributes to crop yield and hence the value of water.

Generally, farming inputs, when applied in optimal quantities at the right times may contribute significantly to the value of water (Oweis and Hachum, 2003). For example, the level of crop yield response to nitrogen may depend on the quantities of water applied and the availability of other nutrients such as phosphorus and potassium in the soil. Research indicates that crop yield response to nitrogen increases with the increase in water supply until a certain level, where further application of these inputs result in decrease of crop yield (Rockström et al., 2003; Oweis and Hachum, 2003). Similarly, when phosphorus in the soil is inadequate, response to nitrogen and applied irrigation water can be constrained (Oweis and Hachum, 2003). The apparently insignificant contributions of these inputs as evaluated using multiple regression models might be as result of: (i) the contribution of some of these variables being already implicit in some of the significant contributing factors as indicated by the correlation coefficients of independent variables (Table 7.3). For example, crop yield (X_6) significantly correlates with the amount of NPK (X_9) applied, suggesting that if the variable crop yield was not included in the regression equation then fertilizer use would likely have registered a significant contribution, and (ii) Unsystematic application of inputs with varying effects on crop yield that might have been difficult to capture from the socio-survey. Fertilizers, seed, pesticides, and labor among other factors also showed a non-significant contribution in a study of water production functions for wheat in the dry region of West Asia and North Africa (UN, 2003).

Table 7.3: Correlation coefficients of the regression variables for Reg1 model

	VW_T	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}
VW_T	1													
X_1	-0.12	1												
X_2	-0.23**	0.46*	1											
X_3	-0.01	0.39*	0.08	1										
X_4	0.00	0.16*	0.26**	0.10	1									
X_5	-0.04	0.31**	0.05	0.11	0.10	1								
X_6	0.81**	0.16*	-0.15	0.04	0.02	0.14	1							
X_7	0.05	-0.44**	-0.48**	-0.06	-0.08	-0.05	-0.07	1						
X_8	-0.02	0.23**	0.12	0.20*	0.02	0.01	0.00	-0.10	1					
X_9	0.27**	-0.10	-0.42**	-0.06	0.00	-0.03	0.30**	0.22**	0.02	1				
X_{10}	0.07	0.00	-0.23**	0.09	-0.20*	-0.08	0.08	-0.04	-0.05	0.05	1			
X_{11}	-0.21**	0.56**	0.34**	0.34**	0.20*	0.00	-0.05	-0.12	0.10	-0.09	-0.01	1		
X_{12}	-0.05	0.17*	-0.04	0.11	0.05	-0.02	-0.03	0.07	0.07	-0.06	0.08	0.01	1	
X_{13}	0.53**	-0.23**	-0.12	0.02	-0.03	-0.22**	0.00	0.14	0.04	0.02	-0.01	-0.16	0.00	1

*, ** significant at 5% and 1% respectively

With the exception of the variable tomato seed use (X_7), which suggested mixed effects among the regression models, irrigation method or technology (X_5), number of fertilizer applications (X_8), plowing methods (X_{11}) and labor use (X_{12}) negatively correlated to the value of water. The use of surface canals was associated with a reduction in the value of water among the models. The negative effect of irrigation method or technology to the value of water could be related to water management practices such as timing and amount of irrigation supplied in surface canal irrigation systems. Timing is related to the control of irrigation, which is inefficient in many surface canal irrigation systems (Zhang, 2003). The number of fertilizer applications (X_8), plowing method (X_{11}), and total labor use (X_{12}) are also negatively correlated to the value of water, all of which are correlated with scheme location (X_1).

More than 95% of variability in the value of water could be explained by estimated regression with the F-test significance level of 0. Although the majority of the variables, excluding scheme location (X_1), crop yield (X_6), and price of tomatoes (X_{13}) did not show a strong relationship with the dependent variable, diagnostic tests of the residuals supported the linear regression assumptions. These assumptions were: linear relationship between dependent and independent variables, independence of the random errors in the predicted variable, constant variance and normality of the errors. The autocorrelation (Durbin-Watson), multicollinearity (TF and VIF) and the outliers' (Cook's and Leverage distances) tests of regression residuals are within general acceptable ranges (Table 7.4). Similarly, normal probability plots of the residuals and the plot of the observed and expected cumulative probability of the residuals are approximately normally distributed about the mean and are homogeneous (Figure 7.1).

Table 7.4: Collinearity, autocorrelation and outliers diagnostic tests

Variable	Reg1		Reg2		Reg3		Reg4	
	Tolerance	VIF	Tolerance	VIF	Tolerance	VIF	Tolerance	VIF
X_1	0.34	2.94	0.34	2.94	0.34	2.94	0.34	2.94
X_2	0.47	2.11	0.47	2.11	0.47	2.11	0.47	2.11
X_3	0.77	1.31	0.77	1.31	0.77	1.31	0.77	1.31
X_4	0.86	1.17	0.86	1.17	0.86	1.17	0.86	1.17
X_5	0.77	1.30	0.77	1.30	0.77	1.30	0.77	1.30
X_6	0.82	1.22	0.82	1.22	0.82	1.22	0.82	1.22
X_7	0.62	1.62	0.62	1.62	0.62	1.62	0.62	1.62
X_8	0.91	1.10	0.91	1.10	0.91	1.10	0.91	1.10
X_9	0.72	1.39	0.72	1.39	0.72	1.39	0.72	1.39
X_{10}	0.87	1.16	0.87	1.16	0.87	1.16	0.87	1.16
X_{11}	0.55	1.83	0.55	1.83	0.55	1.83	0.55	1.83
X_{12}	0.87	1.15	0.87	1.15	0.87	1.15	0.87	1.15
X_{13}	0.89	1.12	0.89	1.12	0.89	1.12	0.89	1.12
Durbin-Watson	1.956		1.968		1.968		1.926	
Cook's distance	0.016		0.018		0.017		0.015	
Leverage statistics	0.110		0.110		0.110		0.110	

TOL > 0.1 and VIF < 10 are considered acceptable, Durbin-Watson, values lies between 0 and 4, a value of 2 indicate there appears to be no autocorrelation. Leverage statistics under 0.2 and Cook's distance <4/n where n is the number of cases are considered acceptable.

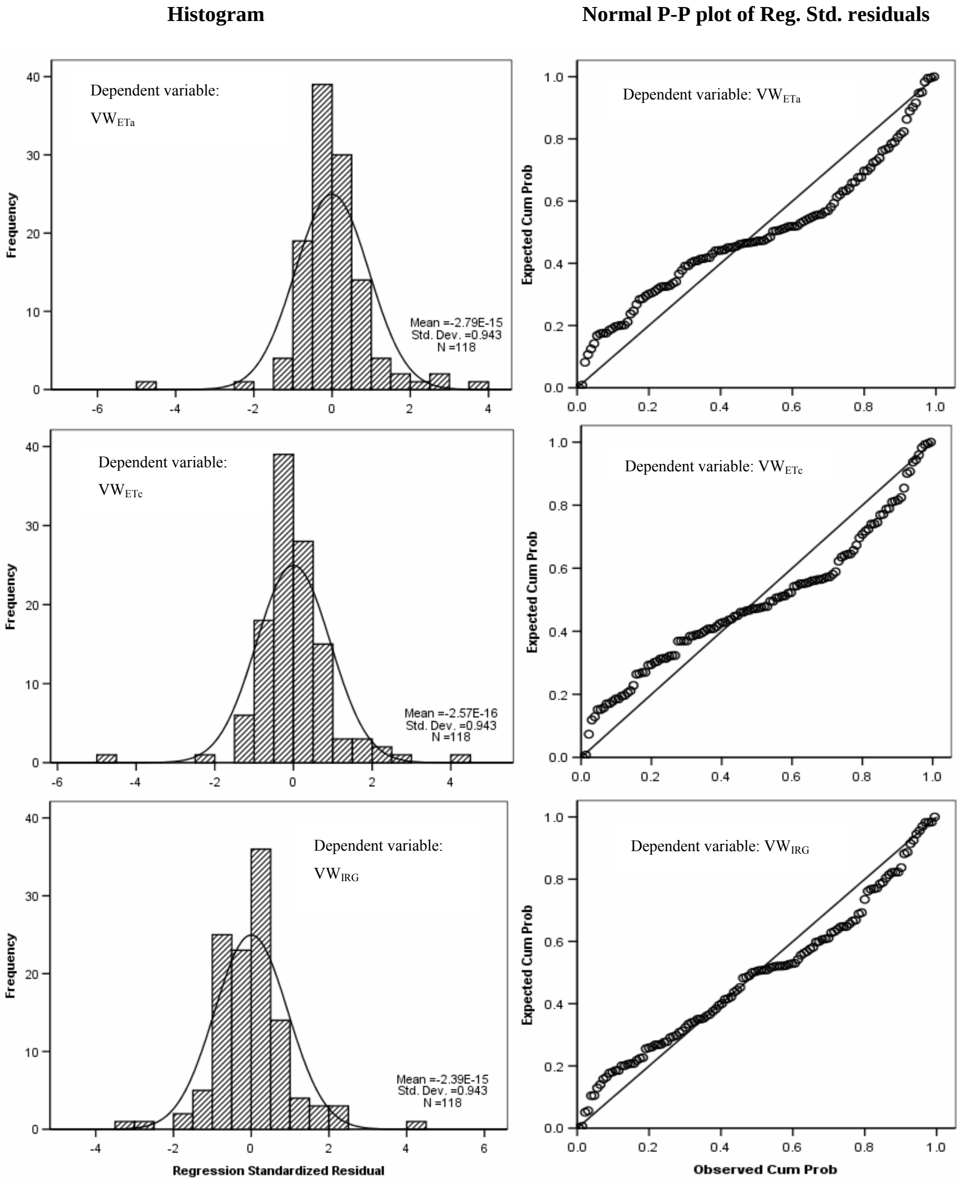

Figure 7.1: Normality and homogeneity tests of the regression residuals for the variables VW_{ETa}, VW_{ETc} and VW_{IRG}

There was a strong relationship between observed and predicted values of water with high correlation coefficients (>97%) for all the models (Figure 7.2). Although the models show underestimation on the lower ranges of observed values, no serious systematic over- or underestimation is observed except for a few extreme points with high values of water.

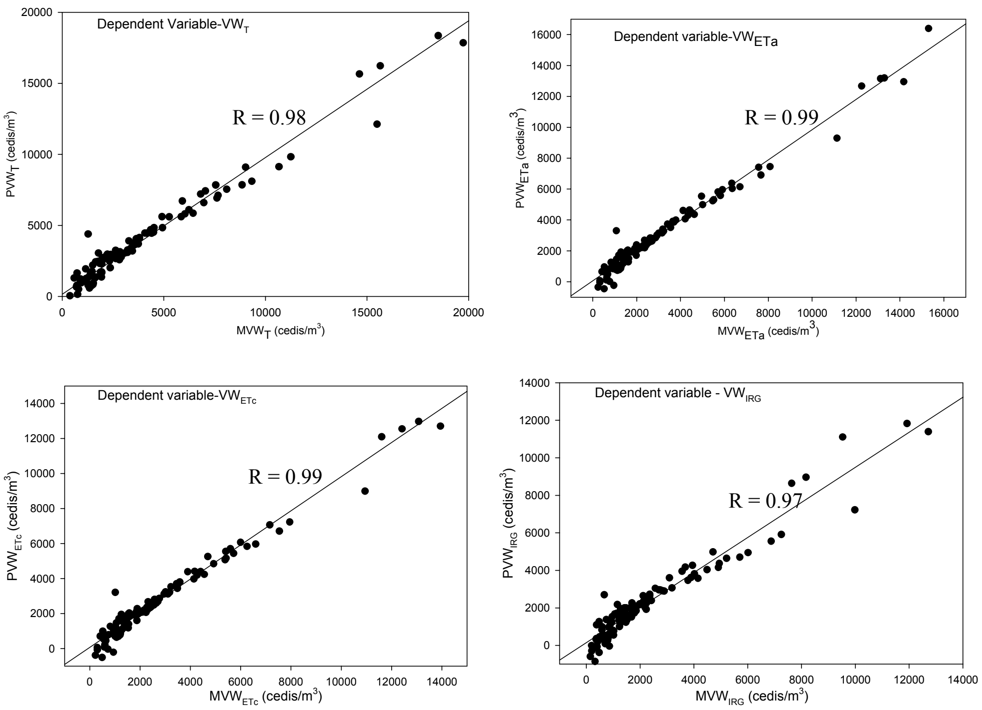

Figure 7.2: Observed and predicted values of water for four dependent variables

7.4 Summary and conclusions

Location of the scheme, crop yield and price of tomatoes were the main factors significantly contributing to the value of water. The variable scheme indicated that factors which are controlled by location characteristics such as soils and climatic conditions can significantly influence the value of water in a particular setting. However, in contrasting irrigation systems factors which are not included in the regression analysis such as the amount of available water resources, water management agencies, i.e. community or parastatal, water distribution and allocation mechanisms may have an important role on influencing the value of water. The fact that other production factors are not significantly associated with the value of water in this study could be due to their contributions being implicit in some of the significant contributing factors, such as crop yield and scheme location.

The current results emphasize the importance of managing factors that enhance crop yield such as the use of improved varieties, application of right quantities of fertilizers and pesticides at the right times, and good land and water management practices in improving the value of water. Price is another important unit which is part of the value of water. Policy instruments that ensure a secure and stable market of harvested tomatoes are be important for avoiding losses of embodied value of water in tomatoes through unjust markets.

8 GENERAL CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Reservoirs are important sources of water supplies for supporting socioeconomic activities in the UER. Irrigation, livestock, and fisheries are the three important reservoir water uses with respect to reservoir water resources management. Efficient management of water resources is hindered by worn-out irrigation canals, inadequate number of water management personnel for medium reservoirs, characteristically small catchment size generating small volumes of runoff, and the lack of technical support for planning of dry season water use in small reservoirs. Although the role of reservoir water in supporting multiple uses is commonly acknowledged, nevertheless planning of water use both in medium and small reservoirs is generally based on water requirements for irrigation supply alone.

The soil water balance at field level was accurately estimated, and the simulated actual crop water use from sample plots were within the range of tomato evapotranspiration estimates in semi-arid tropics appearing in research literature. The soil water balance analysis suggested that plots were over-irrigated by 40 to 70% in the medium reservoirs and 11 to 40% in the small reservoirs. Over-irrigation occurred mainly during the pre-wetting of the plots, which is practiced to facilitate the workability of soils during plowing. Although a large part of this water flowed away from the plots as surface and deep percolation losses, pre-wetting of the soils also contributes to soil moisture storage, which provides security against water shortages or delays in water supply during the subsequent irrigation period. The SWAP model was found to be useful in quantifying the soil water balance components at field level, particularly the groundwater component, which is generally difficult to determine on the basis of general physical measurements. Part of ET_c (13%) at Dorongo was apparently contributed from capillary soil moisture. However, such contribution could have been as a result of leakages and seepage from the reservoir and not entirely from the soil moisture stored in the previous seasons.

Irrigation supply at farm level at Tono was about three times the average ET_c, and more than 60% of the irrigation water flowed out of the farm as surface drainage, groundwater percolation and /or evapotranspiration from non-crop vegetated fields.

Some portion of the surface drainage and groundwater percolation outflows, which are captured and reused in the downstream of the scheme, may not be counted as losses. However, it is apparently difficult conceptually and practically to determine the volume of water reused within the scheme and the water quality issues presented by the recycling of return flows. The irrigation water supply at scheme level at Tono was about six times higher than ET_c. A high ratio of the water released relative to water requirements points to the mismatch between irrigation water supplies and potential crop water use, but also contributes to water loss and thus low WP. As a result, crop water use efficiency was very much lower at Tono (16%) relative to Dorongo (100%). However, the 100% water use efficiency at Dorongo was due to the lower supply of net-irrigation relative to crop water requirement. In spite of the differences in size, water availability, and management and operation between the study sites, such a wide gap in water use efficiency points to a significant potential for improving water management at Tono.

On the basis of a range of well defined WP indicators, physical WP at plot level was higher at Dorongo than at Tono, although variation within sites existed. The WP showed a decreasing trend from WP_T to WP_I underscoring the fact that for a similar obtained crop yield, WP would be higher under transpiration indicator relative to irrigation because not all the amount of irrigated water directly contributes to crop transpiration. The range of values between WP_T and WP_I indicates the likely possible options of increasing WP_I to values close to WP_{ETc}, particularly in the case of over-irrigation. The WP_T is an upper limit which practically cannot be attained under field conditions. The WP values of similar crops at farm and scheme levels at Tono were similar. The difference in WP_{ETc} between the schemes for tomato was mainly due to differences in planting dates and harvested crop yield. Average crop yield at Dorongo was about three times higher than that at Tono. Crop yields at Tono were affected by pests and diseases and late crop planting in the season. Although smaller values of WP than the values (especially for maize and soybean) at farm and scheme level at Tono have been reported under semi-arid and semi-humid climates, WP values from this study are generally low for most of the crops.

There are, however, potentials for improving WP at field, farm, and scheme levels. At field level, WP could be improved by: (i) reducing deep percolation losses resulting from over-irrigation during the period of land preparation at the beginning of the crop season, (ii) good agronomic management practices such as mulching, which reduces direct soil moisture evaporation from exposed soil surfaces that do not directly contribute to crop water use and thus WP. It is important to note that such an increase in WP might potentially be offset by the increased costs of land preparation under dry soil conditions. At farm and scheme levels at Tono, improvement of WP could be achieved by minimizing excess inflows into the system, which results into mismatch between irrigation supplies and crop water requirements. Such reduction of inflows could be easily achieved by implementing irrigation scheduling practices applicable to different crop growth periods. However, implementing a practical irrigation schedule in places like Tono may require additional number of water management personels. At Dorongo, gains in WP at plot and scheme levels could be attained from strategies that enhance crop yield, such as the choice of better crop varieties, and good timing of cropping activities whin the season, pest and disease control, and proper use of fertilizers.

Water, land and capital are the main factors determining the size of tomato plots planted in the dry season in the UER. While in some instances land and water may be available, for instance in medium reservoirs, farmers could be capital constrained limiting them to farm small plots. On the other hand, insufficient water means that farmers have to share land which can be supplied with available water regardless of their capital endowments. Land, capital, water, labor, seed, fertilizers, and pesticides are the main inputs for irrigated dry season tomato farming. Although minimum capital at Tono was twice that at Dorongo, indicating more capital-diverse farmers at Tono than at Dorongo, the mean values of farming inputs per hectare between the study sites were similar. The cost of inputs such as seeds, fertilizers, pesticides, and fuel were uniformly distributed within schemes, although they were slightly higher at Dorongo than at Tono due to higher application rates on small plots. The use and cost of labor for irrigating and harvesting represented about 50% of the total labor use and cost of all the farming activities. While the contributions of labor and non-water inputs to the total production were approximately the same between the sites, a slightly higher contribution for capital at Tono suggests that capital is a more important input at Tono compared to Dorongo. Likewise, the small contribution of labor at the two sites does not imply that labor is less important than other inputs for the dry season irrigated tomatoes farming, but simply that labor is highly underpaid in the study area. The contribution of water to the total value of production was about 58% (Tono) and 64% (Dorongo), indicating that water plays important role for the dry season irrigated tomato farming. The value of water showed a decreasing trend from VW_T to VW_I at both sites, a similar pattern to that depicted under physical WP. The analysis shows that the value of water was not significantly different at 5% significance level between the sites among the indicators used, but it was significantly different at 5% significance level within sites between the various indicators.

The value of water based on irrigation deliveries was a relevant indicator at Dorongo, since part of the irrigation supply which appears as groundwater percolation losses cannot be recovered for reuse within and downstream the scheme and is considered a lost resource from the farmer's point of view. However, at Tono, the value of water based on actual or potential crop water use could be a practical indicator at plot and farm levels, since any surface and groundwater losses could potentially be reused downstream.

A similar value of water for livestock was obtained at the two study sites because it was estimated based on the daily water requirement needed to produce required livestock feeds per TLU. Increased dead storage volume at Tono resulted in a lower value of water for fishery compared to Dorongo. The added values per unit reservoir water from livestock and fisheries were smaller than the value of water for tomato irrigation.

Scheme location, crop yield and price of tomatoes were the main significant factors contributing to the value of water. Scheme location suggested that specific environmental conditions in a given settings can significantly influence the value of water. Although other variables were statistically insignificant, their contribution could have been implicit in some of the significant factors. Apart from improvements in water management strategies, other production factors that enhance crop yields are important for improving the value of water. Good price of harvested tomatoes is an important unit for realizing improvement in the value of water.

8.2 Recommendations

This study shows that WP in medium and small reservoirs in the study region is not better than the few estimates available in semi-arid SSA. However, the estimates obtained here are lower than those reported outside SSA, particularly for vegetables, which are considered high value crops. There is, however, a potential for improving WP in the study area, from the perspectives of both improvements in water management and agronomic practices. Water management improvements may include better crop timing in the season to avoid periods of higher crop water requirements due to higher temperatures, avoiding over-irrigation particularly during land preparation at the beginning of the season, and proper planning of irrigation supplies based on seasonal estimates of crop water requirements. Improved agronomic practices may involve the use of improved seed varieties (e.g., good quality and disease resistant), correct application of agrochemicals (fertilizers and pesticides), and application of mulching especially at the early stages of crop development to reduce soil moisture evaporation from exposed soil surfaces. Provision of government support to ensure a secure market for harvested irrigated produce, especially for perishables such as tomatoes, is essential as an incentive for the farmers to invest in strategies that improve WP.

The SWAP model was instrumental in quantifying the soil water balance components at field level, a key input in WP estimation. However, only the water transport module under simple crop growth was applied. Other options in SWAP include simulation of solute and heat transport, and the application of a detailed crop module that enables simulation of potential maximum crop yield under a specified combination of soil, water and crop parameters. A follow-up study using data of more than one season involving all options available in SWAP will be important for a complete modeling of WP of different crops and for providing information on the effects of management changes in water distribution and allocation on WP.

Water is a critical input in tomato dry season farming in the study region. Although better estimates of the value of water and its contributing factors can be obtained by constructing water production functions, data on water use for a sufficient number of representative elements (farms) and other inputs spanning over more than one production season are necessary. The contribution of land, to which is currently difficult to attach a price due to lack of markets for land, may also need to be considered in future water valuation studies in the region.

The determination of the value of water for livestock uses poses a great challenge to obtaining complete and reliable estimates in the region, because data required in existing livestock WP assessment frameworks are completely lacking. Experimental studies involving different types of livestock, gathering data on livestock inputs and products, and including the negative impacts of livestock in reservoir water resources, might be necessary to fully understand the contribution of reservoir water in livestock production. Further studies are also required to develop tools for assessing the value of water in fisheries, particularly for resolving the ambiguity in the definition of fishery water use under multiple water use systems.

The approach employed in this study can easily be applied to other locations. However, more WP studies from related water systems are required for sound up-scaling of the findings to similar climatic conditions.

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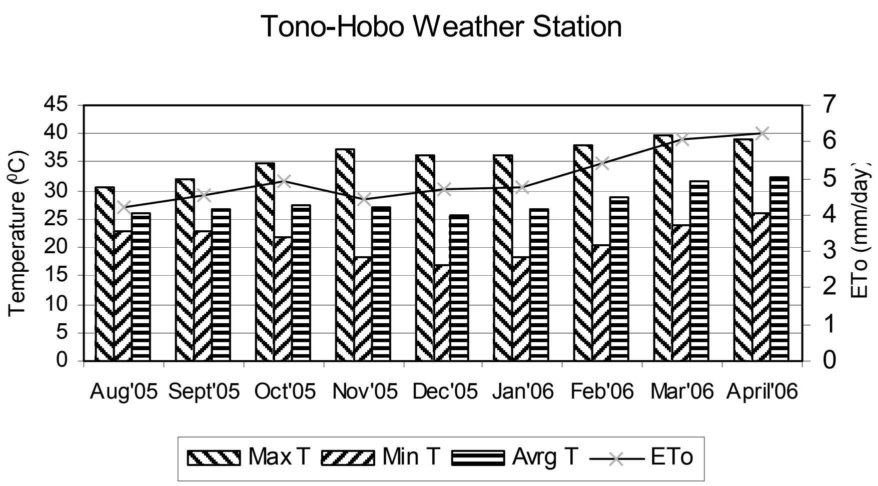
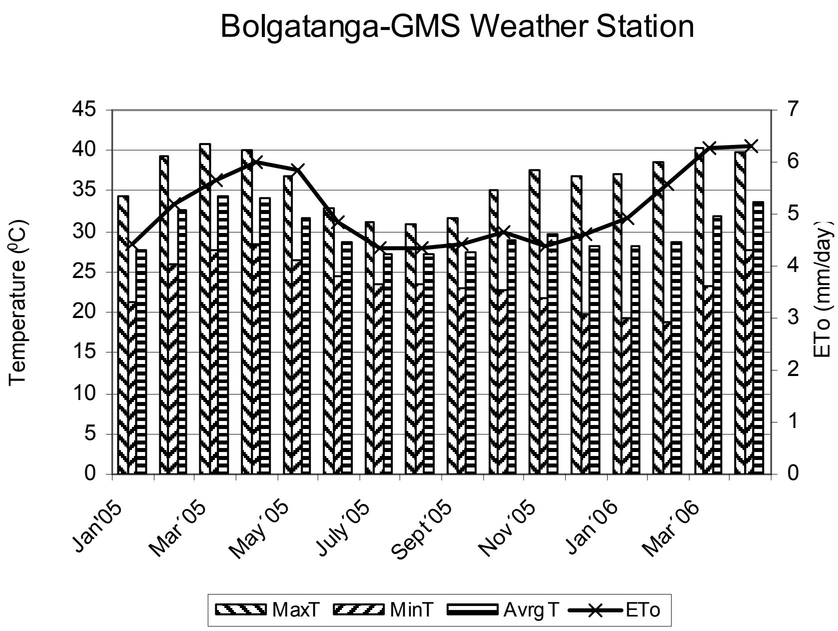
10 APPENDICES

Appendix 10.1: Temperature and potential evapotranspiration (ETo) at Tono and Bolgatanga





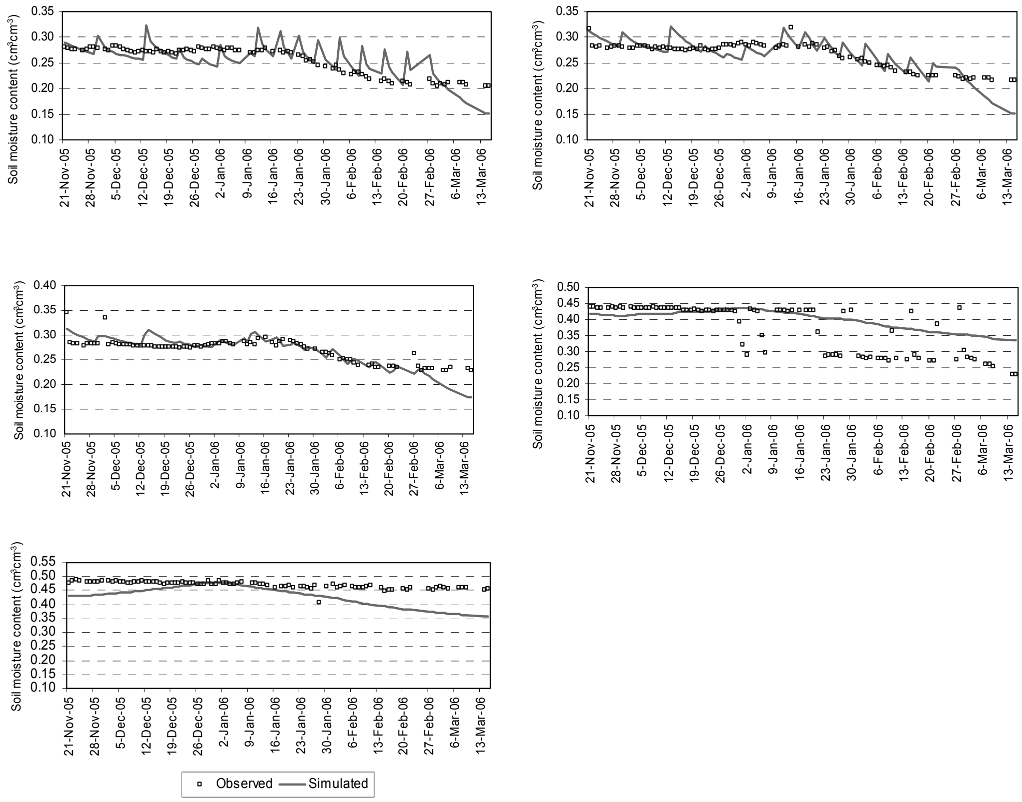
Appendix 10.2: Physical and hydraulic soil properties at Tono and Dorongo schemes in the Upper East Region

Plot No.	Profile Depth (cm)	Soil Texture	Clay (%)	Sand (%)	BD (gcm^{-3})	θ_s (cm^3cm^{-3})	θ_{FC} (cm^3cm^{-3})	θ_{PWP} (cm^3cm^{-3})	K_s (cmd^{-1})
Tono									
1	0-15	Sandy Loam	9.01	70.78	1.46	0.32	0.16	0.08	81.94
	15-40	Silt	8.94	12.96	1.38	0.32	0.31	0.08	42.58
2	0-20	Sandy Loam	10.82	68.14	1.47	0.35	0.18	0.09	81.94
	20-50	Sandy Loam	14.98	68.86	1.49	0.34	0.20	0.11	85.00
Dorongo									
1	0-20	Loam	20.60	42.24	1.44	0.41	0.28	0.14	14.32
	20-43	Clay Loam	34.43	38.42	1.42	0.44	0.34	0.21	12.50
	43-80	Sandy Clay Loam	28.83	46.66	1.46	0.44	0.31	0.19	12.77
	80-120	Sandy Clay Loam	28.44	46.34	1.45	0.49	0.29	0.16	17.75
2	0-20	Loam	12.72	42.02	1.43	0.38	0.25	0.10	27.30
	20-50	Sandy Loam	14.61	55.22	1.46	0.39	0.23	0.11	30.75
	50-90	Loam	24.55	43.26	1.44	0.41	0.30	0.17	12.36
	90-135	Clay Loam	30.60	43.00	1.44	0.49	0.32	0.20	11.02
3	0-15	Sandy Loam	6.65	71.08	1.45	0.39	0.15	0.06	71.15
	15-35	Sandy Loam	12.82	61.74	1.47	0.39	0.20	0.10	42.83
	35-70	Sandy Clay	40.40	48.56	1.47	0.52	0.34	0.23	18.42
	70-120	Clay Loam	34.63	35.14	1.41	0.54	0.35	0.22	9.42
4	0-15	Silt Loam	18.93	16.92	1.37	0.42	0.32	0.13	21.01
	15-55	Clay Loam	33.08	34.58	1.41	0.44	0.34	0.21	9.63
	55-90	Clay Loam	29.25	23.34	1.37	0.54	0.35	0.19	7.21
	90-135	Silt Clay Loam	30.86	12.02	1.32	0.53	0.37	0.19	12.01

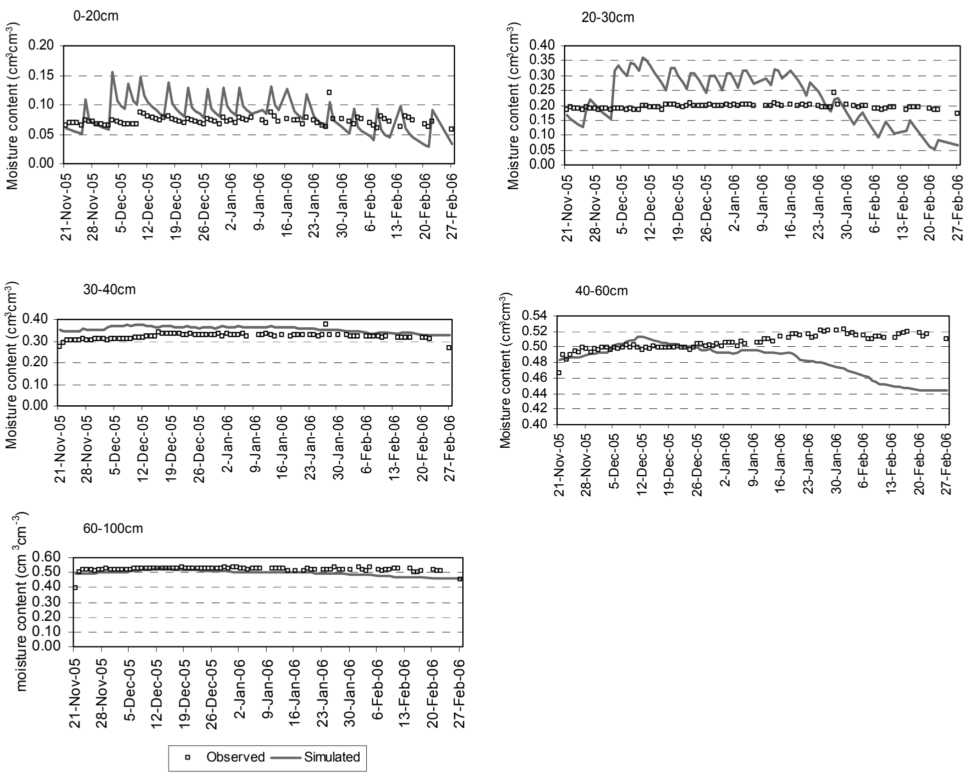
Appendix 10.3: Chemical soil properties at Tono and Dorongo schemes in the Upper East Region

Plot No.	Profile Depth (cm)	Soil Texture	pH (1:1 H_2O)	Organic matter (%)	Organic carbon (%)	Total N (%)	Exchangeable Cations (me/100g)				T.E.B	Exch. A (Al+H)	C.E.C (me/100g)	Base Saturation (%)	Available-Brays	
							Ca	Mg	K	Na					ppmP	ppmK
Tono																
1	0-15	Sandy Loam	5.00	1.28	0.74	0.07	2.80	1.04	0.22	0.20	4.26	0.20	4.46	95.52	9.87	121.78
	15-40	Silt	5.30	1.12	0.65	0.06	2.40	0.72	0.14	0.08	3.34	0.20	3.84	94.35	7.75	82.29
2	0-20	Sandy Loam	6.50	0.64	0.37	0.02	4.80	1.44	0.35	0.18	6.77	0.08	6.85	98.83	7.24	161.28
	20-50	Sandy Loam	6.78	0.61	0.35	0.02	5.12	1.44	0.31	0.20	7.07	0.08	7.15	98.88	3.10	148.11
Dorongo																
1	0-20	Loam	7.48	0.67	0.39	0.02	7.20	12.32	0.60	0.53	20.65	0.05	20.70	99.76	2.33	174.44
	20-43	Clay Loam	7.64	0.48	0.27	0.03	19.52	3.68	0.54	0.49	24.23	0.08	24.31	99.67	0.88	144.82
	43-80	Sandy Clay Loam	8.18	0.18	0.10	0.01	13.28	8.32	0.53	0.43	22.56	0.08	22.64	99.65	1.71	131.66
	80-120	Sandy Clay Loam	7.47	0.17	0.10	0.01	9.12	11.20	0.54	0.55	21.41	0.05	21.46	99.77	3.36	148.11
2	0-20	Loam	5.93	0.93	0.54	0.06	7.68	2.88	0.41	0.21	11.18	0.10	11.28	99.11	7.65	128.36
	20-50	Sandy Loam	6.92	0.91	0.53	0.04	8.80	5.12	0.22	0.29	14.43	0.08	14.51	99.45	7.18	121.78
	50-90	Loam	7.78	0.17	0.10	0.01	11.52	9.76	0.50	0.20	21.98	0.08	22.06	99.64	2.48	154.7
	90-135	Clay Loam	8.05	0.11	0.06	0.01	17.44	10.88	0.70	0.40	29.42	0.05	29.47	99.83	1.55	187.61
3	0-15	Sandy Loam	4.80	1.34	0.78	0.07	2.72	4.00	0.24	0.03	6.99	0.35	7.34	95.23	9.82	148.11
	15-35	Sandy Loam	4.87	0.63	0.37	0.02	4.32	1.44	0.23	0.17	6.16	0.45	6.61	93.19	3.93	95.45
	35-70	Sandy Clay	6.19	0.60	0.35	0.04	13.44	6.88	0.64	0.42	21.38	0.13	21.51	99.40	1.09	144.82
	70-120	Clay Loam	6.50	0.44	0.25	0.01	14.88	8.00	0.58	0.48	23.94	0.13	24.07	99.46	1.60	143.18
4	0-15	Silt Loam	6.37	1.91	1.11	0.12	16.64	1.96	0.89	0.31	19.80	0.10	19.90	99.50	3.67	171.15
	15-55	Clay Loam	7.09	1.37	0.80	0.06	8.96	13.12	0.50	0.50	23.08	0.10	23.18	99.57	2.07	166.22
	55-90	Clay Loam	6.94	0.49	0.28	0.03	10.08	7.68	0.42	0.44	18.62	0.08	18.70	99.57	1.14	148.11
	90-135	Silt Clay Loam	6.50	0.46	0.27	0.01	9.92	8.56	0.48	0.39	19.35	0.10	19.45	99.49	2.17	151.4

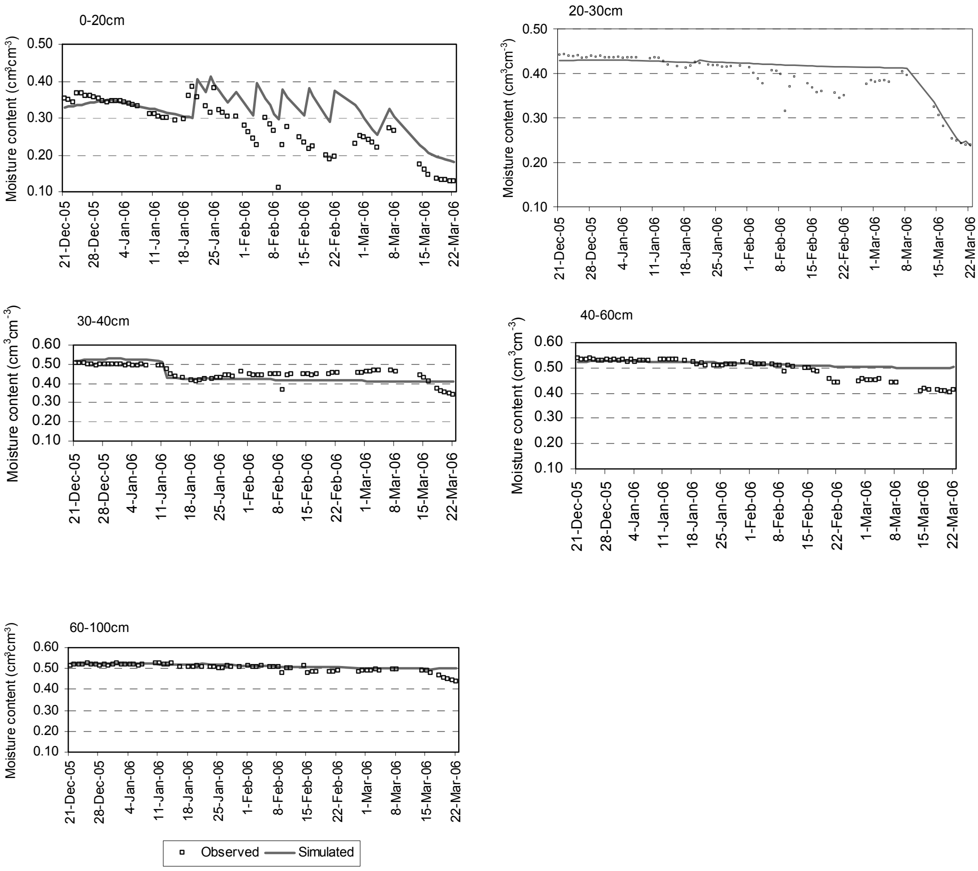
Appendix 10:4: Observed and simulated soil moisture profiles for plot1 at Dorongo



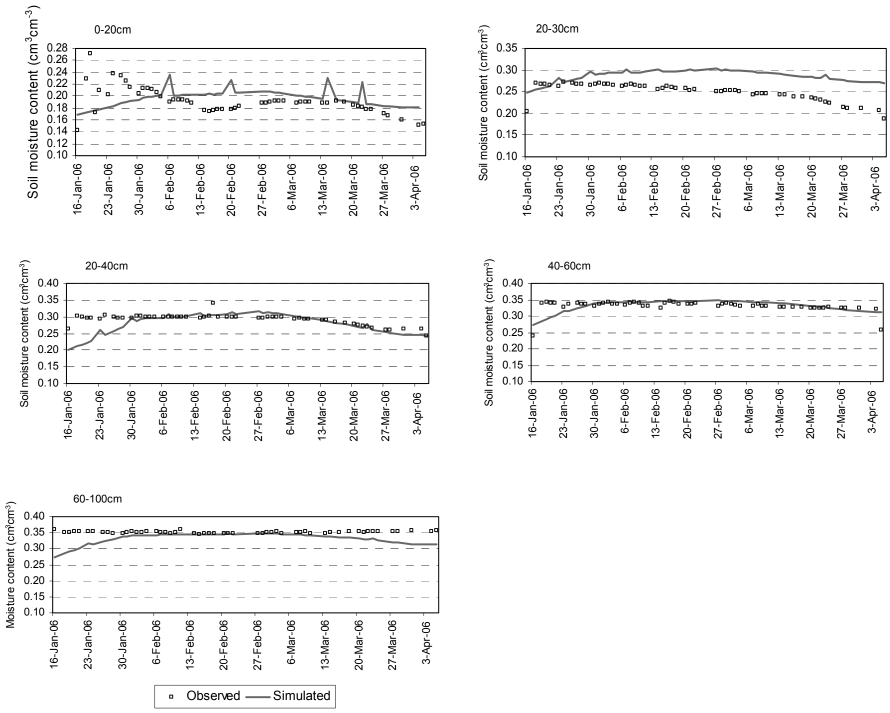
Appendix 10.5: Observed and simulated soil moisture profiles for plot3 at Dorongo



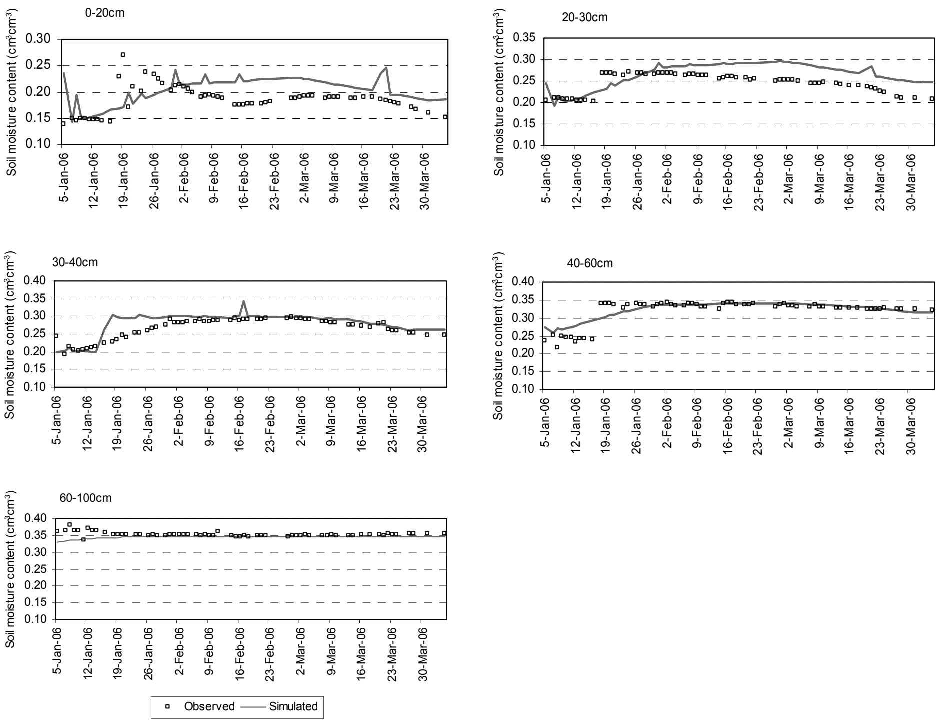
Appendix 10.6: Observed and simulated soil moisture profiles for plot4 at Dorongo



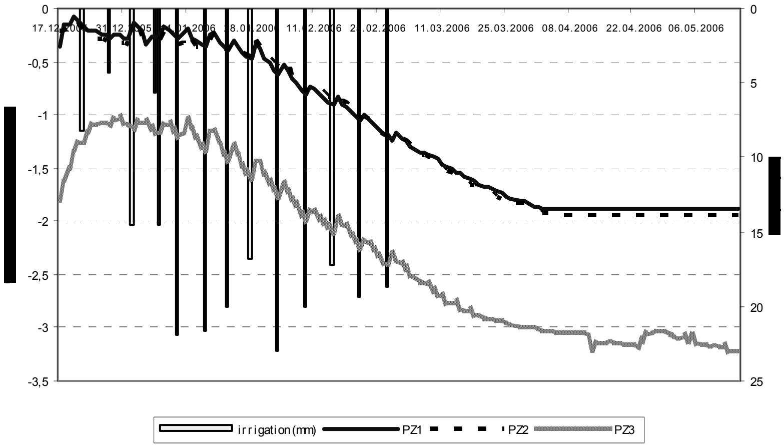
Appendix 10.7: Observed and simulated soil moisture profiles for plot1 at Tono



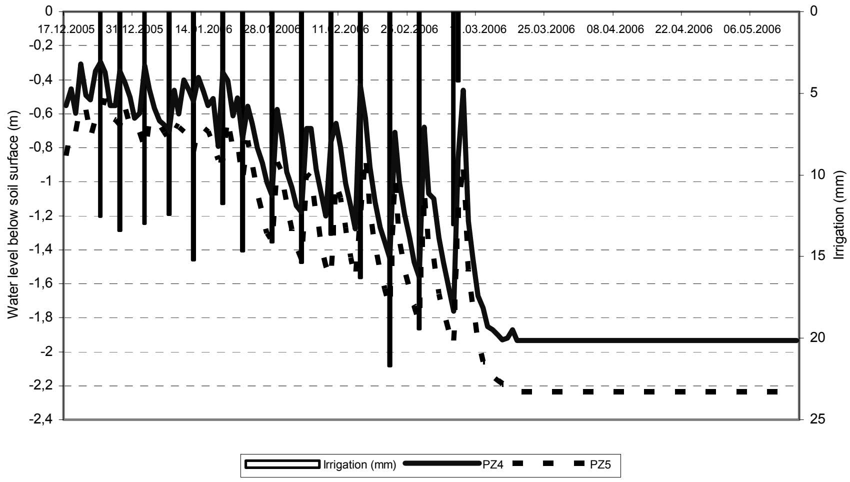
Appendix 10.8: Observed and simulated soil moisture profiles for plot2 at Tono



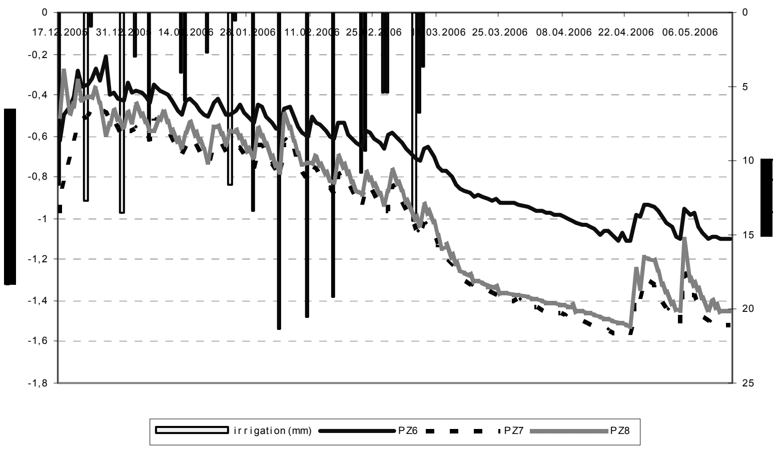
Appendix 10.9: Shallow groundwater-irrigation interactions in piezometers (PZ) on plot1 during the 2005/06 dry season farming at Dorongo scheme



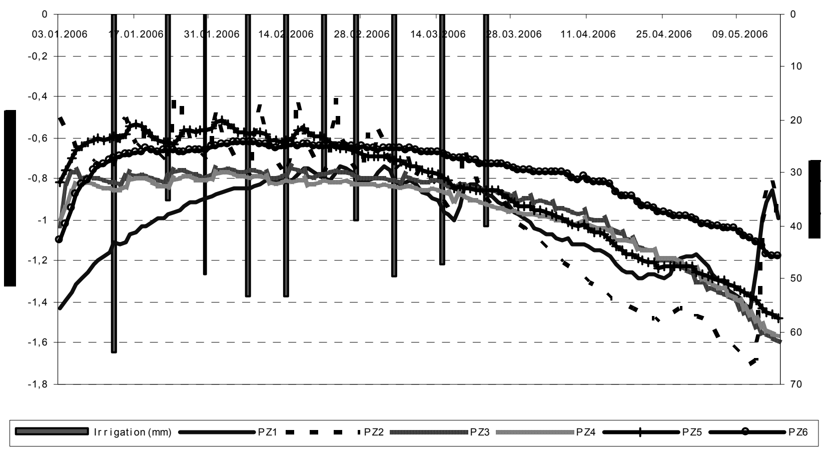
Appendix 10.10: Shallow groundwater-irrigation interactions in piezometers (PZ) on plot2 during the 2005/06 dry season farming at Dorongo scheme



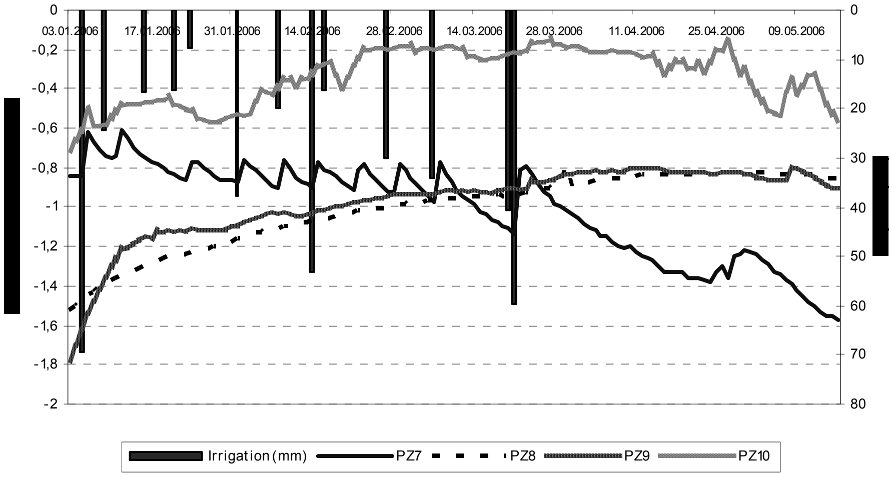
Appendix 10.11: Shallow groundwater-irrigation interactions in piezometers (PZ) on plot4 during the 2005/06 dry season farming at Dorongo scheme



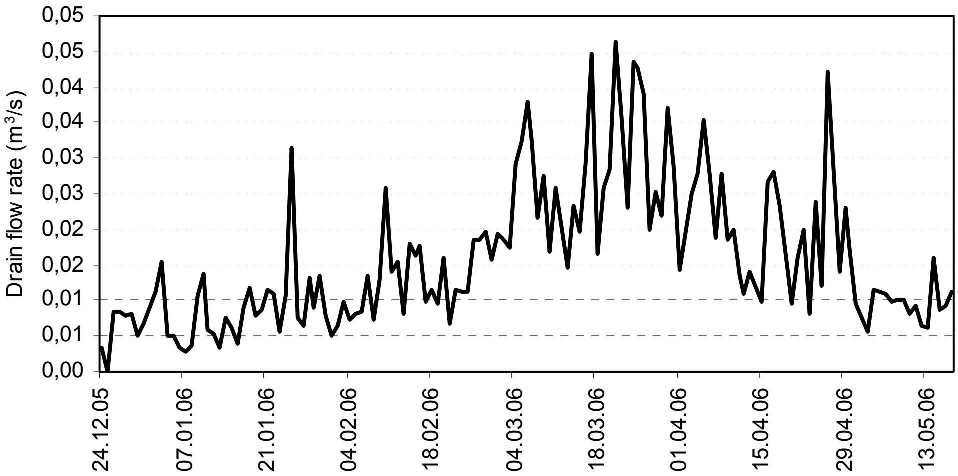
Appendix 10.12: Shallow groundwater-irrigation interactions in piezometers (PZ) on plot1 during the 2005/06 dry season farming at Zone-M farm in Tono scheme



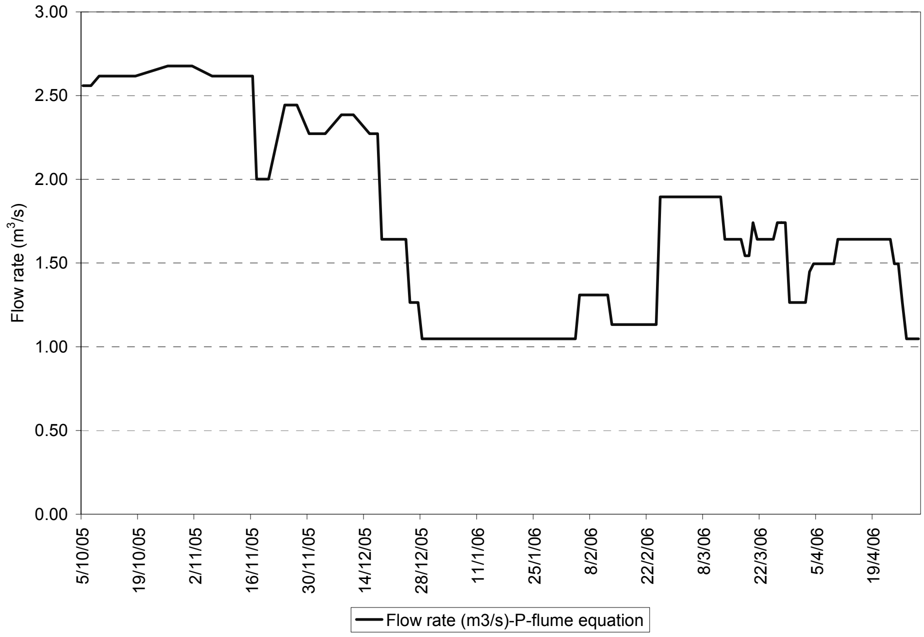
Appendix 10.13: Shallow groundwater-irrigation interactions in piezometers (PZ) on plot1 during the 2005/06 dry season farming at Zone-M farm in Tono scheme



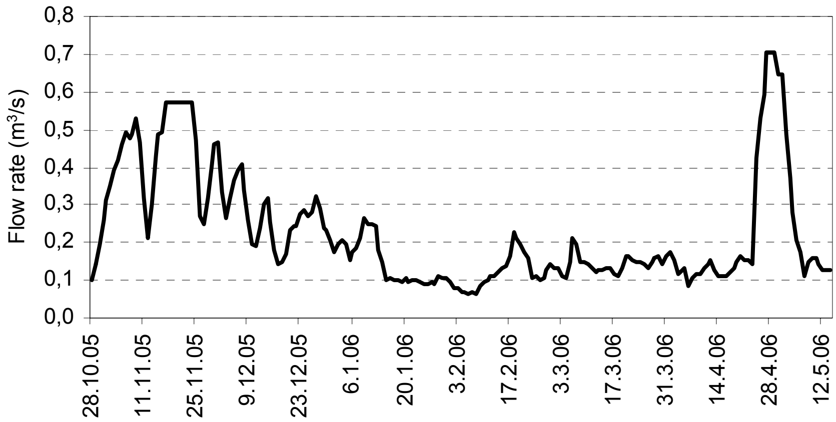
Appendix 10.14: Total drainage outflows at Zone-M farm at Tono during 2005/06 dry season



Appendix 10.15: Irrigation diversion from Tono Dam during 2005/06 dry season



Appendix 10.16: Main drainage outflows at Tono scheme during 2005/06 dry season



Appendix 10:17: Important farming inputs at Tono and Dorongo during 2005/06 dry season

Household Number	Familysize	Plowing method	Variety of tomato planted	Irrigation method	Household farm assets (¢)	Plot (ha)	Fuel use (l/ha)	Yield (kg/ha)	seed use (kg/ha)	fertilizer (kg/ha)	Pesticides (l, kg/ha)	Labor use (man-days/ha)
1	16	Tractor	Petomech VF	Surface canal	90810.42	0.13		11224.49	0.23	80.40	4.83	64.25
2	8	Tractor	Petomech VF	Surface canal	7200.00	0.03		11663.77	0.26	00.82	6.02	86.09
3	15	Tractor	Petomech VF	Pump	86108.00	0.09		14636.32	0.27	30.53	5.31	77.11
4	14	Human labor	Petomech VF	Pump	301900.00	0.20	100.84	13177.70	0.24	04.20	2.52	79.63
5	6	Oxen/bullock	No name	Surface canal	131150.00	0.05		7260.00	0.25	00.00	5.00	72.33
6	16	Tractor	Petomech VF	Surface canal	98253.87	0.13		11224.49	0.23	80.36	4.83	62.17
7	4	Oxen/bullock	Petomech & no name	Surface canal	65948.55	0.17		8117.27	0.29	30.03	3.94	90.94
8	8	Tractor	Petomech VF	Pump	369750.60	0.22	90.09	4905.36	0.24	06.75	3.38	88.77
9	5	Human labor	Petomech VF	Pump	39535.41	0.10	50.00	2178.00	0.25	00.00	2.50	86.28
10	5	Human labor	Petomech VF	Surface canal	115387.40	0.07		10816.13	0.25	58.68	3.72	76.06
11	7	Human labor	Petomech & Tropimech	Surface canal	61072.91	0.15		8046.47	0.20	07.47	4.07	97.01
12	20	Tractor	Petomech & no name	Pump & surface	78692.45	0.34	88.57	4072.51	0.27	53.57	2.30	69.22
13	8	Human labor	Petomech VF	Surface canal	94240.48	0.09		1951.61	0.27	37.63	5.38	87.43
14	12	Oxen/bullock	Petomech VF	Surface canal	129297.30	0.08		20692.04	0.20	06.41	6.06	74.71
15	5	Tractor	Petomech VF	Surface canal	139000.00	0.26		4215.33	0.28	83.85	1.55	74.89
16	22	Oxen/bullock and Tractor	Petomech VF	Pump & surface	329926.40	0.69	28.91	6190.70	0.20	33.58	4.77	67.14
17	6	Human labor	Petomech VF	Surface canal	170000.00	0.19		4867.83	0.24	15.77	7.74	95.28
18	10	Tractor	Petomech VF	Pump	77988.81	0.24	84.94	14800.66	0.15	24.72	3.19	63.35
19	6	Human labor	Petomech VF	Surface canal	335000.00	0.20		30584.59	0.28	51.09	4.90	73.33
20	10	Tractor	Petomech VF	Pump	310000.00	0.27	72.82	9515.90	0.29	46.14	3.09	84.85
21	8	Human labor	No name	Surface canal	213560.00	0.04		13447.56	0.23	63.07	5.79	67.59
22	13	Human labor	No name	Surface canal	102000.00	0.04		11346.97	0.14	63.07	1.42	76.82

Household Number	Familysize	Plowing method	Variety of tomato planted	Irrigation method	Household farm assets (¢)	Plot (ha)	Fuel use (l/ha)	Yield (kg/ha)	seed use (kg/ha)	fertilizer (kg/ha)	Pesticides (l, kg/ha)	Labor use (man-days/ha)
23	7	Human labor	No name	Surface canal	99359.80	0.21		3092.99	0.27	73.37	1.18	67.86
24	9	Tractor	Tropimech	Surface canal	35182.50	0.09		8684.21	0.27	43.71	2.72	68.34
25	12	Tractor	No name	Pump & surface	78862.71	0.37	54.05	6475.14	0.27	56.08	8.11	72.55
26	7	Tractor	Petomech VF	Pump & surface	175802.50	0.37	54.66	4563.42	0.27	12.42	2.73	57.66
27	10	Tractor	Petomech VF	Surface canal	68290.00	0.10		19319.79	0.26	21.79	5.22	86.49
28	20	Tractor	Tropimech	Surface canal	35248.00	0.17		4737.17	0.29	35.00	5.80	68.50
29	8	Tractor	Petomech VF	Surface canal	101582.00	0.17		4631.90	0.29	35.00	2.90	65.61
30	7	Tractor	Petomech VF	Surface canal	116940.00	0.20		6575.16	0.29	03.15	5.53	68.68
31	11	Human labor	Petomech & Tropimech	Surface canal	42759.88	0.06		18836.09	0.27	89.66	3.93	108.93
32	13	Tractor	Petomech & Tropimech	Pump	109790.00	0.21	96.65	8771.27	0.28	83.27	1.45	82.19
33	17	Tractor	No name	Surface canal	151376.90	0.21		5834.08	0.27	72.70	4.73	66.67
34	8	Tractor	Petomech & Tropimech	Surface canal	333879.80	0.25		3222.24	0.28	05.50	1.01	77.45
35	5	Oxen/bullock	Tropimech	Surface canal	20687.50	0.03		26027.72	0.20	97.93	4.98	91.15
36	4	Human labor	Tropimech	Surface canal	45732.73	0.09		27130.68	0.29	83.91	2.92	65.57
37	10	Human/oxen/Tractor	Petomech VF	Surface canal	93991.52	0.08		34797.14	0.22	85.78	4.86	83.81
38	10	Human labor	No name	Surface canal	53537.18	0.05		8018.82	0.20	409.08	1.02	90.34
39	7	Human labor	No name	Surface canal	137100.00	0.11		6387.58	0.22	439.92	4.40	81.44
40	6	Human labor	Tropimech/no name	Surface canal	65000.00	0.04		28454.83	0.23	576.38	4.03	60.99
41	7	Human labor	No name	Pump	19289.16	0.16	51.28	5119.23	0.19	480.77	4.01	75.43
42	11	Tractor	Petomech & no name	Pump	58437.04	0.13	78.37	6258.62	0.24	587.77	5.49	87.04
43	10	Tractor	Petomech VF	Surface canal	55501.64	0.26		10116.78	0.26	580.62	2.42	73.47
44	10	Tractor	Petomech VF	Pump & surface	781452.40	0.50	40.38	6595.85	0.22	529.97	4.04	91.15
45	7	Tractor	Petomech VF	Pump	365675.50	0.40	99.09	3237.22	0.22	557.37	3.72	75.81
46	8	Human labor	Petomech VF	Surface canal	6700.00	0.03		24885.74	0.26	476.08	4.76	86.46
47	14	Oxen/bullock	No name	Pump	64248.70	0.27	73.30	19156.94	0.25	458.11	4.21	81.58
48	8	Oxen/bullock	No name	Surface canal	460435.50	0.07		14532.92	0.19	556.05	3.71	71.21

Household Number	Familysize	Plowing method	Variety of tomato planted	Irrigation method	Household farm assets (¢)	Plot (ha)	Fuel use (l/ha)	Yield (kg/ha)	seed use (kg/ha)	fertilizer (kg/ha)	Pesticides (l, kg/ha)	Labor use (man-days/ha)
49	22	Oxen/bullock	Petomech VF	Surface canal	30026.93	0.06		12125.46	0.21	417.54	2.09	76.85
50	10	Human labor	Tropimech	Surface canal	313000.00	0.04		41910.61	0.25	465.55	3.10	75.88
51	9	Tractor	Petomech VF	Pump & surface	140551.10	0.26	78.39	23048.70	0.26	489.93	6.27	66.33
52	9	Human labor	Petomech VF	Surface canal	35120.68	0.09		7809.81	0.27	403.40	5.38	68.45
53	5	Tractor	Petomech VF	Pump	89760.00	0.03	83.33	10551.20	0.27	416.67	4.17	85.67
54	6	Tractor	Petomech VF	Surface canal	49295.68	0.22		5674.74	0.27	517.27	4.60	87.10
55	4	Tractor	No name	Pump	157343.30	0.13	78.37	23668.97	0.16	587.77	5.88	83.93
56	4	Human labor	Petomech & Tropimech	Surface canal	46380.00	0.19		10928.91	0.19	537.63	4.03	71.28
57	5	Human labor	No name	Surface canal	32150.00	0.06		6050.00	0.28	416.67	5.21	71.55
58	3	Human labor	Petomech VF	Surface canal	42787.50	0.04		16140.51	0.22	555.80	3.69	80.78
59	6	Oxen/bullock and Tractor	Petomech VF	Surface canal	74090.00	0.14		10640.29	0.21	469.17	5.36	70.34
60	4	Oxen/bullock and Tractor	Petomech VF	Surface canal	60890.00	0.14		8666.78	0.21	519.03	2.60	76.26
61	11	Tractor	Petomech VF	Surface canal	15407.15	0.04		83490.00	0.01	625.00	1.68	72.23
62	6	Tractor	Petomech VF	Surface canal	125000.00	0.08		15427.50	0.02	625.00	6.25	72.35
63	11	Tractor	Petomech VF	Surface canal	102638.40	0.65		3574.15	0.10	307.69	3.08	79.77
64	5	Tractor	Petomech VF	Surface canal	674499.60	0.40		7078.50	0.10	500.00	2.50	85.39
65	6	Tractor	Petomech VF	Surface canal	14295.00	0.06		9680.00	0.01	833.33	4.17	80.84
66	14	Tractor	Petomech VF	Surface canal	48180.00	1.00		2904.00	0.10	200.00	7.00	80.62
67	9	Tractor	Rfuego	Surface canal	27383.75	0.04		4537.50	0.01	625.00	6.25	65.32
68	8	Human labor	Petomech VF	Surface canal	182797.80	0.04		21780.00	0.01	625.00	6.25	79.89
69	6	Tractor	Petomech VF	Surface canal	176410.90	0.04		36300.00	0.01	625.00	6.25	75.98
70	3	Tractor	Petomech VF	Surface canal	72280.00	0.10		31944.00	0.03	750.00	2.50	89.84
71	5	Tractor	Petomech VF	Surface canal	7320.00	0.80		4719.00	0.10	375.00	10.00	67.87
72	9	Tractor	Petomech VF	Surface canal	53644.55	0.04		65340.00	0.01	625.00	6.25	69.58
73	5	Tractor	Petomech VF	Surface canal	24150.00	0.40		9438.00	0.10	500.00	1.88	85.98
74	8	Human labor	Petomech VF	Surface canal	173801.40	0.04		29040.00	0.01	625.00	.	75.76
75	9	Tractor	Petomech VF	Surface canal	84920.00	0.04		63525.00	0.01	625.00	6.25	75.72
76	4	Tractor	Petomech VF	Surface canal	26164.50	0.40		3630.00	0.10	375.00	.	83.23
77	4	Tractor	Petomech VF	Surface canal	59396.25	0.40		1452.00	0.10	437.50	1.25	69.55

Household Number	Familysize	Plowing method	Variety of tomato planted	Irrigation method	Household farm assets (¢)	Plot (ha)	Fuel use (l/ha)	Yield (kg/ha)	seed use (kg/ha)	fertilizer (kg/ha)	Pesticides (l, kg/ha)	Labor use (man-days/ha)
78	6	Tractor	Petomech VF	Surface canal	40192.50	0.40		4900.50	0.10	500.00	1.25	82.16
79	9	Tractor	Petomech VF	Surface canal	24248.36	0.81		1837.41	0.15	555.56	1.23	74.32
80	4	Tractor	Petomech VF	Surface canal	32082.50	0.40		2722.50	0.10	375.00	1.25	80.32
81	3	Tractor	Petomech VF	Surface canal	225796.50	4.50		2081.20	0.67	244.44	1.78	73.18
82	7	Tractor	Petomech & ST Lius	Surface canal	315491.10	1.30		24013.85	0.22	770.77	1.92	75.50
83	3	Tractor	Petomech & no name	Surface canal	88229.38	2.60		28844.54	0.40	230.77	1.28	83.30
84	1	Tractor	Petomech & no name	Surface canal	257727.30	2.09		3091.58	0.33	358.85	2.63	90.22
85	6	Tractor	Petomech VF	Surface canal	96771.89	1.23		10842.86	0.21	649.35	5.48	69.25
86	5	Tractor	Petomech VF	Surface canal	108162.10	1.02		9252.94	0.18	441.18	4.90	75.66
87	5	Tractor	Petomech VF	Surface canal	122250.00	0.40		4719.00	0.10	625.00	1.88	71.36
88	16				38536.73							
89	6	Tractor	Petomech VF	Surface canal	225196.00	0.40		5989.50	0.10	250.00	5.00	77.65
90	5	Tractor	Petomech & Tropimech	Surface canal	46335.20	1.20		20328.00	0.20	375.00	3.96	59.24
91	3	Tractor	Tropimech/no name	Pump	835330.10	1.30		16083.69	0.20	692.31	4.42	81.65
92	3	Tractor	Petomech VF	Surface canal	91470.59	0.40		13431.00	0.10	437.50	3.25	75.20
93	3	Tractor	Petomech VF	Surface canal	169909.10	0.40		7296.30	0.10	375.00	3.13	88.85
94	10	Tractor	Petomech VF	Surface canal	137547.70	0.40		7986.00	0.10	750.00	3.13	73.51
95	4	Tractor	Petomech VF	Pump	447876.10	2.80	21.43	8686.07	0.50	357.14	1.61	70.12
96	3	Tractor	Petomech VF	Surface canal	285758.20	0.40		16879.50	0.10	500.00	3.00	94.93
97	5	Tractor	Petomech VF	Pump	445949.50	0.57	105.63	3962.32	0.10	352.11	8.36	87.00
98	11				1374519.00	1.25					2.20	
99	4	Tractor	Petomech VF	Surface canal	296667.90	0.80		9982.50	0.10	500.00	1.88	87.17
100	4	Tractor	Petomech VF	Surface canal	978840.50	1.00		13068.00	0.10	450.00	4.50	74.76
101	3	Tractor	Petomech VF	Surface canal	275000.00	0.40		11979.00	0.10	625.00	3.75	90.77
102	9	Tractor	Petomech VF	Pump & surface	558310.90	0.80	25.00	11253.00	0.20	500.00	3.13	82.86
103	8	Tractor	Petomech VF	Surface canal	44404.00	0.40		22506.00	0.10	500.00	6.25	94.18
104	3	Tractor	Petomech VF	Pump & surface	376904.30	1.20	66.67	27164.50	0.20	416.67	1.67	65.61
105	4	Tractor	Petomech VF	Surface canal	114666.10	1.75		8712.00	0.30	228.57	2.29	69.55
106	5	Tractor	Petomech VF	Surface canal	56390.00	0.80		9438.00	0.10	250.00	5.00	82.10

Household Number	Familysize	Plowing method	Variety of tomato planted	Irrigation method	Household farm assets (¢)	Plot (ha)	Fuel use (l/ha)	Yield (kg/ha)	seed use (kg/ha)	fertilizer (kg/ha)	Pesticides (l, kg/ha)	Labor use (man-days/ha)
107	8	Tractor	Petomech VF	Surface canal	75600.00	0.40		16698.00	0.10	500.00	2.50	96.22
108	7	Tractor	Petomech VF	Surface canal	54891.54	0.80		13612.50	0.10	375.00	5.31	76.10
109	9	Tractor	Petomech VF	Surface canal	71467.73	0.40		30492.00	0.10	500.00	2.50	81.25
110	9	Tractor	Petomech VF	Surface canal	136340.00	0.40		17787.00	0.10	500.00	5.00	88.20
111	11	Tractor	Petomech VF	Surface canal	276225.50	0.40		22324.50	0.10	250.00	2.50	84.03
112	7	Tractor	Petomech VF	Surface canal	196720.00	0.80		15609.00	0.10	375.00	2.50	83.69
113	6	Tractor	Petomech VF	Surface canal	240074.60	0.60		13310.00	0.10	333.33	8.33	84.07
114	5	Tractor	Petomech VF	Surface canal	48575.00	0.40		13612.50	0.10	500.00	7.50	96.13
115	7	Tractor	Petomech VF	Surface canal	96479.35	0.40		12705.00	0.10	500.00	5.00	101.17
116	7	Tractor	Petomech VF	Surface canal	103584.20	0.80		5626.50	0.10	250.00	2.50	80.94
117	7	Tractor	Petomech VF	Surface canal	71074.00	0.40		12523.50	0.10	500.00	7.50	97.97
118	4	Tractor	Petomech VF	Surface canal	56735.00	0.40		17061.00	0.10	500.00	7.50	81.89
119	7	Tractor	Petomech VF	Pump	3594840.00	2.00	90.00	13794.00	0.30	250.00	2.50	85.56
120	6	Tractor	Petomech VF	Surface canal	108469.10	0.40		17787.00	0.10	500.00	7.50	97.11

ACKNOWLEDGEMENTS

I am grateful to the almighty God for the life and strength during the period of this study. My sincere gratitude to Prof. Dr. P.L.G. Vlek for supervising this study. I also thank Prof. Dr-Ing. Dr. h.c. J.J. Bogardi for agreeing to be my second supervisor. The guidance and constructive criticism I received from my tutor Dr. Charles Rodgers during the entire period of this study is whole- heartedly appreciated.

I thank ZEF for providing a good and supporting study environment in Bonn. The support of the international doctoral program at ZEF, particularly of Dr. Manske, and the wonderful, immeasurable help of Mrs. Rosemarie Zabel with administrative and social encounters in Bonn is highly appreciated. I am grateful to Sabine Aengenendt-Baer, Miryam Buttenhoff, Bernadette Olderdissen and Doris Fuss for their services at the ZEFc secretariat. I also thank Mrs. Margaret Jendi for proof reading the thesis and Dr. Constanze Leemhuis for translating my abstract into German.

I express my sincere gratitude to the German Federal Ministry for Economic Cooperation and Development (BMZ) for its generous financial support, which was obtained through DAAD and GTZ. I thank the GLOWA Volta project for the logistical fieldwork support and for the assistance I received from the project staff. I would like to acknowledge the support of the GLOWA Volta project coordinators in Ghana, Dr. Boubacar Barry and Dr. Mathias Fosu for their great help during my field data collection. I thank Dr. Wolfram Laube for introducing me to the study area and for the useful discussions about the study sites. I thank Dr. Adetola Adeoti for her contributions to the design of my field survey questionnaire. I am also grateful to the GLOWA Volta project drivers in Ghana, particularly Mr. Benjamin Heywood, the late Mr. Michael Akwa, and Mr. David Ochard, whose knowledge of the research area was instrumental in my daily field activities. I am very grateful to Mr. Alhaji Issa A. Bukari and Mr. Thomas Sumboh, managing and deputy managing directors of ICOUR; Mr. Dickson D. Bagbara and Eng. Sebastian Bagna, Tono project manager and project engineer for allowing me to conduct field data collection in the Tono irrigation project and for their cooperation. I also thank my field assistants, Thomas Abagna, Stephen Atimoliga, and Thomas Anaya whose hard work and cooperation resulted to a successful field data collection. I am also thankful for the cooperation I received from the community members at the Tono and Dorongo schemes, and the Bolgatanga MOFA office.

The company of my the colleagues at ZEF, Kofi Nyarko, John Kasina, Dilys Sefakor, Damas Phillip, Nhamo Nhamo, Jean-Pierre, Hong-Ching Goh, Daniel Callo-Concha, Jacqueline Qarcia-Yi, Adelina Mensa, Emmanuel Obubie, Raymond Kasei, and Dhalia Hassan was very important. My gratitude to Drs. Japhet Kashaigili and Victor Afari-Sefa for reading some of my chapters and to Dr. Machibya Magayane for his constant encouragements. I am equally grateful to Dr. Ranvir Singh for his help on how to link SWAP to PEST.

To my parents, Cecilia Udama and the late Victor Chogimembe Mdemu, and to my uncle, Eng. Constantine Mwatima Mhelela, I say thank you for providing me with the opportunity to walk this academic road. I also thank all my brothers and sisters for their unflattering support in my academic life. Last but not least, I thank my wife, Immakulata Komba for shouldering the burden of care of our children, William, Kenneth, and Martin, during my absence and to the children for being able to cope without the paternal guidance.