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ABSTRACT

The design of relevant adaptation strategies for water users in irrigation schemes in drylands of Sub-Saharan Africa requires up-to-date information about the current performance of these schemes in view of rapid changes in climate and land use, population growth, and competing water demands. The entire system of two (a small- and a medium-scale) irrigation schemes shared by multiple users in the Upper East region of Ghana were examined, including the water reservoir, water conveyance and distribution network, cropping fields, and management entity. First, multi-level performance indicators with relevance to water delivery, water utilization, and agricultural production were adapted and applied based on measurements of meteorological, soil and groundwater parameters, irrigation water inputs, crop management and yields for two rainy and dry seasons during 2014–2016 in prevalent cropping systems. For field-level evaluation, the FAO AquaCrop model was applied to develop an improved year-round irrigation schedule for dry-season cultivation of tomato and to assess a possibility for supplemental irrigation of maize in the rainy season under “wet” and “dry” climate scenarios. Finally, a scenario-based analysis of irrigation performance was conducted at scheme scale for the period of 2015–2030 using the Water Evaluation and Planning System (WEAP), a decision support modeling tool. These modeling scenarios considered the observed rainfall variability, introduction of supplemental irrigation in the rainy season, irrigable area expansion, and system efficiency improvement.

Technical factors, such as underutilized reservoir storage capacity and deteriorated conditions of water delivery infrastructure strongly undermined the irrigation system performance. In particular, the medium-scale irrigation scheme utilized less than 40% of total storage, whereas the small-scale scheme utilized about 70% of the storage. The examination of field-level water management practices suggests that an application efficiency of 58–68% is achievable in both schemes by improving the irrigation scheduling of the major crops. Overall system efficiency can be increased from 50% to 68% by reducing water conveyance network losses and by eliminating over-irrigation of fields. The AquaCrop simulations show that improved irrigation schedule for dry-season tomato cultivation would result in a water saving of 130–1,325 mm compared to traditional irrigation practices, accompanied by approximately 4–14% increase in tomato yield. Supplemental irrigation of maize would require 107–126 mm of water in periods of low rainfall and frequent dry spells, and 88–105 mm in periods of high rainfall and rare dry spells. Therefore, year-round irrigation may be feasible, using water saved in dry-season tomato cultivation for supplemental irrigation of maize in the rainy season. However, as predicted by the WEAP analysis, supplemental irrigation in the small-scale scheme could be possible only if the rise in water demand is counterbalanced by about 10% increase in the system efficiency and by setting limits on the cultivation of the water-intensive tomato crop in the dry season. The unavailability of long-term historical data at present prevents the calibration and validation of the WEAP model in Ghana but the conducted scenario analysis sets the framework for further evaluation of the potential water scarcity adaptation options. Overall, the integrated, whole-system approach is essential in the assessment of suitable options for improving reservoir operations and adapting to water scarcity in Sub-Saharan Africa.

Bewertung der Leistung von Stausee-gespeisten Bewässerungssystemen in der Upper East Region, Ghana

KURZFASSUNG

Vor dem Hintergrund des fortschreitenden Klimawandels, der dynamischen Veränderungen der Landnutzung, des starken Bevölkerungswachstums und des sich verschärfenden Wettbewerbs um Wasserressourcen, erfordert die Entwicklung geeigneter Anpassungsstrategien für die Wassernutzung in Trockengebieten südlich der Sahara insbesondere aktuelle Informationen über die derzeitige Qualität des Managements von bestehenden Bewässerungssystemen. Für eine kleine und eine mittelgroße Bewässerungs-Einheit mit Mehrfachnutzung in der Upper East Region in Ghana wurde jeweils das Gesamt-System (und dessen Management) bestehend aus Wasserspeicher, Zuleitungs- sowie Verteilungs(kanal)netz und Anbauflächen untersucht. Zunächst wurden mehrstufige Indikatoren zur Erfassung der Qualität der Bewässerungsdurchführung (in Bezug auf: Wasserverteilung, Wassernutzung, landwirtschaftliche Produktion) ausgewählt, strukturiert und angewendet. Die Anwendung basierte auf Messungen von Größen aus den Bereichen Meteorologie, Boden, Grundwasser, Bewässerungswasser, landwirtschaftliche Aktivitäten und Erträge in zwei Regen- und Trockenzeiten in den Jahren 2014–2016 in Bezug auf relevante Anbausysteme. Auf der Ebene der bewässerten Felder wurde das FAO AquaCrop-Modell zur Erarbeitung ganzjähriger Bewässerungspläne genutzt, die sowohl die Bewässerung zum Anbau von Tomaten in der Trockenzeit erlauben als auch die Beurteilung der ergänzenden Bewässerung von Mais in der Regenzeit unter "nassen" und "trockenen" Klimaszenarien in die Untersuchungen einbeziehen. Schließlich wurde eine Szenarien-gestützte Analyse der Bewässerung für den Zeitraum 2015–2030 auf der Ebene der beiden Bewässerungseinheiten durchgeführt, wozu mit dem WEAP (Water Evaluation and Planning System) ein Modell zur Entscheidungsunterstützung eingesetzt wurde. Die modellierten Szenarien berücksichtigten die beobachtete Niederschlagsvariabilität, die Option zur Einführung ergänzender Bewässerung in der Regenzeit, die Bewässerungsfläche und die Verbesserung der Bewässerungseffizienz.

Technische Faktoren – wie vor allem die unzureichende Nutzung der Kapazitäten der Wasserspeicher und der schlechte Zustand der Wasserversorgungsinfrastruktur – beeinträchtigten die Durchführung der Bewässerung in erheblichem Ausmaß. In dem mittelgroßen Bewässerungssystem wurden weniger als 40% der Kapazität des Wasserspeichers genutzt, wohingegen in dem kleinen System 70% der Speicherkapazität in Anspruch genommen wurden. Die Untersuchung des Wassermanagements auf der Feldebene deutet darauf hin, dass in beiden Systemen eine Effizienz der Feldaufleitung von 58–68% erreicht werden kann, wenn die Steuerung der Bewässerung (angemessene Bewässerungsmengen und –zeitpunkte) für die wichtigsten Nutzpflanzen verbessert wird. Die Effizienz der gesamten Bewässerungseinheit kann von 50% auf 68% erhöht werden, indem die Transportverluste in den Kanälen reduziert und die Überbewässerung von Feldern vermieden werden. Die Simulationen mit dem AquaCrop-Model zeigen, dass ein verbesserter Bewässerungsplan für den Anbau von Tomaten in der Trockenzeit neben

einer Wassereinsparung von 130–1 325 mm (im Vergleich zu traditionellen Bewässerungspraktiken), auch gleichzeitig einen etwa 4- bis 14 prozentigen Anstieg des Ertrages bewirken würde. Die zusätzliche und ergänzende Bewässerung von Mais in der Regenzeit würde 107–126 mm Wasser in Perioden mit geringem Niederschlag und häufigen Trockenperioden bzw. 88–105 mm in Perioden mit hohem Niederschlag und seltenen Trockenperioden erfordern. Daher ist eine ganzjährige Bewässerung realisierbar, wenn das Wasser für die zusätzliche Bewässerung von Mais in der Regenzeit aus Einsparungen in der Bewässerung von Tomaten in der Trockenzeit gedeckt wird. Die Simulationen mit dem WEAP-Modell sagen allerdings voraus, dass eine ergänzende Bewässerung in der kleinen Bewässerungseinheit nur dann möglich wird, wenn der zusätzliche Bedarf an Bewässerungswasser durch einen Anstieg der Systemeffizienz um etwa 10% und die Begrenzung der Flächen für den wasserintensiven Anbau von Tomaten in der Trockenzeit kompensiert wird. Die Tatsache, dass historische Langzeitdaten in den Untersuchungsgebieten derzeit nicht verfügbar sind, verhindert die Kalibrierung und Validierung des WEAP-Modells in Ghana. Dennoch bieten die simulierten Szenarien und deren Analysen einen geeigneten Rahmen für weitergehende Untersuchungen zum Potenzial der Anpassungsoptionen an Wasserknappheit im Untersuchungsgebiet. Zusammenfassend erweist sich der integrierte, ganzheitliche und system-basierte Ansatz als geeignet und bedeutsam für die Einschätzung angemessener Optionen zur Verbesserung des Betriebs von Wasserspeichern als Maßnahme zur Anpassung an die Wasserknappheit in Subsahara-Afrika.

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LIST OF ACRONYMS

AAL	Annual activity level
AAS	Atomic absorption spectrophotometer
AUWD	Annual unmet water demand
AWD	Agricultural water demand
AWUR	Annual water use rate
BD	Bongo downslope well
BF	Bongo Field
BIS	Bongo irrigation scheme
BL	Bongo left well
BM	Bongo mid-slope well
BNF	Bongo Nyariga field
BNF2	Bongo Nyariga Field 2 well
BNJ	Bongo Nyariga Junction well
BNM	Bongo Nyariga middle well
BoNF	Bolga Nyariga field
BoN	Bolga Nyariga well
BR	Bongo right well
BU	Bongo upslope well
DAP	Days after planting
FAO	Food and Agriculture Organization
FDS	Frequency of dry spells
GIDA	Ghana Irrigation Development Authority
GR	Gauge reading
GWCL	Ghana Water Company Limited
ICOUR	Irrigation Company of the Upper Region
IWRM	Integrated Water Resources Management
LACOSREP	Land Conservation and Smallholder Rehabilitation Project
M	Millet

MOFA	Ministry of Food and Agriculture
S	Sorghum
SDG	Sustainable Development Goal
SMC	Soil moisture content
SSA	Sub-Saharan Africa
TDR	Time Domain Reflectometry
TLU	Tropical Livestock Unit
TRMM	Tropical Rainfall Measuring Mission
UER	Upper East region
VF	Vea Field
VF1	Vea Field 1 well
VIS	Vea irrigation scheme
VU	Vea upslope well
WASCAL	West African Science Service Center on Climate Change and Adapted Land Use
WEAP	Water Evaluation And Planning System
WUA	Water Users Association

LIST OF SYMBOLS AND UNITS

Δ	Slope of the saturation vapor pressure-temperature relationship	kPa °C^{-1}
A	Flooded area	m^2
a	Cross-sectional area	m^2
AGB	Total aboveground biomass	Mg ha^{-1}
b	Length of weir crest	M
Ca	Exchangeable calcium	cmol kg^{-1}
CC	Canopy cover	%
CEC	Cation exchange capacity	cmol kg^{-1}
C_p	Specific heat of the air	MJ kg^{-1} °C^{-1}
CY	Crop yield	Mg ha^{-1}
d	Willmott's index of agreement	
DM	Aboveground dry matter	Mg ha^{-1}
DWI	Daily water intake	m^3
DY	Dry yield	Mg ha^{-1}
E	Elevation	M
E_a	Field application efficiency	%
e_a	Actual vapor pressure	kPa
EA	Exchangeable acidity	cmol kg^{-1}
EF	Nash-Sutcliffe model efficiency coefficient	
E_n	Network efficiency	%
E_s	Overall system efficiency	%
e_s	Saturated vapor pressure	kPa
ET_o	Reference evapotranspiration	mm day^{-1}
FC	Field capacity	%
f_o	Initial infiltration capacity	mm h^{-1}
f_p	Infiltration capacity	mm h^{-1}
FY	Fresh yield	Mg ha^{-1}

G	Soil heat flux	W m^{-2}
GIA	Gross irrigation amount	m^3
h	Height of water above weir crest	M
HI	Harvest index	
K	Exchangeable potassium	cmol kg^{-1}
k_c	Crop coefficient	
K_{sat}	Saturated hydraulic conductivity	mm day^{-1}
L	Total length of canal	M
LAI	Leaf area index	
LWD	Livestock water demand	m^3
Mg	Exchangeable magnesium	cmol kg^{-1}
N	Total nitrogen	%
Na	Exchangeable sodium	cmol kg^{-1}
NIR	Net irrigation requirement	Mm
NRMSE	Normalized root mean square error	%
OC	Organic carbon	%
OM	Organic matter	%
P	Available phosphorus	Ppm
P	Wetted perimeter	M
PD	Plant density	plant m^{-2}
PWP	Permanent wilting point	%
Q	Discharge	m^3 s^{-1}
Q_i	Initial discharge	m^3 s^{-1}
R	Hydraulic radius	M
R^2	Coefficient of determination	
r_a	Aerodynamic resistance	s m^{-1}
r_c	Crop resistance	s m^{-1}
RD	Maximum rooting depth	M
R_n	Net radiation	W m^{-2}
R_s	Solar radiation	W m^{-2}

RH	Relative humidity	%
RMSE	Root mean square error	
RS	Row spacing	M
S	Slope of canal bed	
SAT	Saturation	%
S_l	Seepage losses	$m^3 s^{-1}$
S_r	Seepage loss rate	$m^3 m^{-2} s^{-1}$
T	Temperature	°C
TAW	Total available water	%
T_{max}	Maximum temperature	°C
T_{min}	Minimum temperature	°C
TEB	Total exchangeable bases	cmol kg^{-1}
T_r	Relative transpiration	
V	Storage or volume	m^3
WAI	Water availability index	
W_p	Crop-water productivity	kg m^{-3}
γ_a	Psychrometric constant	kPa $°C^{-1}$
λ_w	Latent heat of vaporization	MJ kg^{-1}
ρ_a	Mean air density at constant pressure	kg m^{-3}

1 INTRODUCTION

1.1 Background and problem statement

Doubling agricultural productivity and incomes as well as strengthening the climate change adaption capacity of smallholders is required in order to achieve food security in Sub-Saharan Africa (SSA) by the year 2030 (Barakat et al., 2015; Griggs et al., 2013). About 60% of the population of SSA lives in rural communities with smallholder farming as the primary source of livelihood. Rainfed agriculture practiced on about 80% of the global agricultural land contributes 60–70% to the global food basket, and 81% in SSA (Rockström and Barron, 2007). Currently, the total global agricultural water demand (AWD) is estimated at 6,800 km^3 $year^{-1}$ and an additional 5,600 km^3 $year^{-1}$ would be needed by 2050 to eradicate malnourishment and satisfy the expected food demand of the world's 9 billion population (Rockström, 2003; Rockström and Barron, 2007). Of this additional AWD, 450–2,300 km^3 $year^{-1}$ would be needed in SSA alone (Rockström, 2003; Rockström and Barron, 2007). In the meantime, the high rainfall variability and water scarcity due to climate change is expected to worsen in SSA, with ripple effects on crop water productivity (Boko et al., 2007; de Bruijn and van Dijk, 2006; Sylla et al., 2016). The high rainfall variability disincentivizes farmers' investments in sustainable land management practices, use of improved seeds, pest and disease control, etc., with further adverse impacts on food security (Rockström and Barron, 2007; Sanfo et al., 2017). With the high dependence on rainfed crop production in most parts of SSA, rainfall variability coupled with low-fertility soils results in a yield gap, as the average grain yield ranges between 1–2 Mg ha^{-1} (Adwubi et al., 2009; Kranjac-Berisavljevic et al., 2014; Rockström and Barron, 2007; You et al., 2011). Furthermore, observed rising temperature and frequent warm spells in SSA since 1960 (Boko et al., 2007; New et al., 2006) have the propensity of increasing crop water demand (due to rising evapotranspiration), thereby reducing water productivity during periods of low rainfall (Molden et al., 2010; Sekyi-Annan et al., 2017; Teixeira and Bassoi, 2009) and hence increase the need for supplemental irrigation (Sanfo et al., 2017; Zwart and Bastiaanssen, 2004).

As it stands, achieving food security in SSA is hardly attainable without the inclusion of improved irrigation management strategies which ensure year-round water availability for smallholder agricultural systems, thus making them resilient to the impact of climate change and variability. However, only 4% of the cultivated area in the SSA is under irrigation, which is rather low as compared to 37% in Asia, 28% in northern Africa, and 6% in the whole of Africa (McCartney and Smakhtin, 2010; You et al., 2011). The sustainability of more than 19,000 small- and medium-scale irrigation schemes constructed all over SSA to provide water for crop irrigation and other multiple users including livestock, fishery and drinking water needs is compromised owing to population growth, changing climate and land use, increasing water demands, and the poor condition of the infrastructure (Acheampong et al., 2014; Mutambara et al., 2016; Venot et al., 2012). There should not only be an expansion of the irrigation system in SSA to meet current and future food needs (Alam, 1991; You et al., 2011), but also, and more importantly, the existing irrigation schemes need to be strengthened by improving current water management practices, assisting farmers in implementing these strategies, rehabilitating the systems thereby enabling development of sustainable adaptation strategies for coping with climate, environmental and demographic changes. To ensure food security globally, and in SSA in particular, coordinated development of rainfed and irrigated farming systems is recommended (Rockström and Barron, 2007). Considering that most of the irrigation schemes in water-scarce regions serve multiple purposes, the development of appropriate location- and context-specific irrigation schedules for crops by water managers and their adoption by farmers will not only increase crop-water productivity (W_p) (Pereira, 2007; Rockström and Barron, 2007; Teixeira and Bassoi, 2009), but also enhance water availability (through water savings) for the multiple sectors. Moreover, the appropriate irrigation scheduling should allow for supplemental irrigation in the rainy season as a result of improved efficiency of on-farm water applications during the dry season (El Afandi et al., 2010; Molden et al., 2010; Sekyi-Annan et al., 2018a; Zwart and Bastiaanssen, 2004). As long as increased irrigation efficiency is accompanied by yield increments, this provides incentives for irrigators to engage in sustainable land management strategies (Ali and Talukder, 2008; Molden et al., 2010; Pereira, 2007; Rockström and Barron, 2007).

Since both under- and over-irrigation compromise crop yields, irrigation scheduling for crop cultivation has to be properly developed, taking into consideration the prevailing irrigation infrastructure (e.g., method of irrigation practiced) and the biophysical characteristics of the irrigation site (Ali and Talukder, 2008; Sekyi-Annan et al., 2018a). In order to realize the full benefits of improved irrigation schedules, namely high crop-water productivity (W_p) and increased water availability, irrigation infrastructure should be upgraded with the flow-measuring and -dosage structures, while the deteriorating water conveyance and distribution subsystems need to be repaired (Ali and Talukder, 2008; Pereira, 2007).

In addition, institutional innovations of the currently siloed (sector-based) water management are required in reservoir-based irrigation schemes, particularly in view of water-related conflicts among water users during periods of water shortage (Acheampong et al., 2014; de Bruin et al., 2015). A number of studies in SSA (Agyenim and Gupta, 2012; Höllermann et al., 2010) pointed out that the adoption of the principles of integrated water resources management in the operation of multi-purpose reservoirs leads to equitable water allocation and prevents water-related conflicts. Consequently, some major aspects of this concept have been applied in this current research by employing the whole-system approach in the performance analysis including the entire irrigation system, coordinating competing water demands and multiple water users, as well as the consideration of the long-term perspective of reservoir operation.

1.2 Irrigation scheme development in Sub-Saharan Africa

SSA has had a long history of irrigation development as the quest for year-round water availability for agriculture has always been part of the governments' discourse on rural economic development (Mutambara et al., 2016; Venot et al., 2012). The discourse on sustainable irrigation development has become even more prominent in recent times due to the anticipated impact of climate change in the region (Boko et al., 2007;

McCartney and Smakhtin, 2010). Concerns about a rising water scarcity (drought) in the dry season in most parts of SSA coupled with the low productivity of rainfed agriculture and the high population growth (about 3% annually) causing food insecurity, poverty and rural-urban migration compelled the governments to implement interventions (Mutambara et al., 2016). These interventions were meant to ensure water availability for year-round crop production, animal husbandry, fishery, domestic water needs (and in some cases for hydropower generation) in order to improve the rural economy and curb the aforementioned societal problems (Alam, 1991; McCartney and Smakhtin, 2010; McCully and Pottinger, 2009; World Bank, 2011).

In the early 20^{th} century, the construction of multi-purpose large-scale irrigation schemes with a storage capacity of more than 3 million m^3 and an irrigable area of about 10,000 ha was seen by policy makers as the panacea for enhancing agricultural production under water scarcity conditions and thus rural development (Alam, 1991; Burney et al., 2013; McCartney and Smakhtin, 2010). Hence, governments in SSA countries with the support of international agencies and donors made huge investments in the construction of large-scale irrigation schemes with more than 66% of the schemes located in Sudan, Nigeria, South Africa and Madagascar (Asres, 2016; Mutambara et al., 2016; You et al., 2011). Most of these were surface irrigation schemes operating by gravity flow or motorized pump irrigation, and a few schemes were equipped with sprinklers (Alam, 1991; Frenken, 2005). The construction contracts were awarded to large global contractors without involving the beneficiary communities (Mutambara et al., 2016). After the construction, the operation and maintenance responsibilities were undertaken by government institutions (Alam, 1991). Underperformance of the schemes has been recorded and attributed to poor design and construction, weak management, poor coordination among government agencies in charge of the sector, lack of routine maintenance works, and lack of the sense of ownership on the part of the beneficiary communities, who perceived the irrigation schemes as government's assets (Alam, 1991; Mutambara et al., 2016).

Consequently, small- and medium-scale schemes were constructed in the 1960s and 1970s in many SSA countries (Venot et al., 2012). This time round, the potential beneficiary communities were persuaded to contribute to the construction of the schemes with labor force and local construction materials in order to instil the sense of ownership and also to reduce the construction costs (Alam, 1991; Venot et al., 2012). The medium-scale schemes were managed by either a parastatal organisation or a private company, whereas the small-scale schemes were managed by Water Users Associations (WUAs), which are community-based organisations composed of the beneficiaries of the infrastructure. In most of the small-scale schemes, the WUAs were trained priror to assuming the tasks of the scheme water management (Venot et al., 2012). Most of the schemes initially performed well for a few decades but in the long run either underperformed or completely failed owing to inadequate financial capacity of the WUA to conduct maintenance works, poor technical and managerial skills owing to the lack of training of new members of the WUA, and lack of regular technical and institutional support from governmental agencies (Acheampong et al., 2014; Djagba et al., 2014; Venot et al., 2012). Mutambara et al. (2016) argued that a contributory factor to the poor performance of the small- and medium-scale schemes in SSA was the governments' perception of the construction of irrigation schemes as social welfare projects without introducing any water-use fees as a means of capital cost recovery. The latter is commonly practiced in South East Asia where irrigation schemes perform comparatively well (Mukherji et al., 2012). Consequently, the approach to irrigation scheme management adopted by governments in SSA countries and scheme managers rendered the operations of the irrigation schemes unsustainable (Mutambara et al., 2016). Moreover, the poor performance of small- and medium-scale irrigation schemes in northern Gambia, arid and semi-arid lands in Kenya, northern Ghana, Zimbabwe, South Africa, Mozambique, Ethiopia, Niger, Tanzania and in several other countries in SSA are due to deteriorated infrastructure or total abandonment requiring rehabilitation (Acheampong et al., 2014; Berhane et al., 2016; Djagba et al., 2014; Mutambara et al., 2016; Venot et al., 2012).

The government of Ghana in collaboration with donor agencies, non-governmental organisations and the Catholic missions invested significantly in the construction of more than 500 multi-purpose small- and medium-scale reservoir-based irrigation schemes in the 1960s and 1970s in the Upper East, Upper West and Northern regions of the country. Over 220 of these schemes are in the Upper East region (UER) alone (Adwubi et al., 2009; Venot et al., 2012). Of these, the small-scale schemes in the UER have storage capacities in the range of 0.005–1 million m^3 and irrigable areas of < 100 ha (Venot et al., 2012). The two medium-scale schemes have storage capacities ranging between 17 and 95 million m^3 and irrigable areas > 800 ha. Until 1998, these schemes were managed by the government through the Ghana Irrigation Development Authority (GIDA) under the auspices of the Ministry of Food and Agriculture (MOFA). The lack of involvement of the beneficiary communities in the management activities resulted in under-performance and eventual deterioration of the infrastructure (Acheampong et al., 2014). In 1998 and 1999, under the Land Conservation and Smallholder Rehabilitation Project (LACOSREP) phases I and II, most of these schemes were rehabilitated with the formation of WUAs to handle the operation and maintenance responsibilities in order to ensure effective utilization and management of the infrastructure (Venot et al., 2012). The two medium-scale irrigation schemes, namely Tono and Vea, are managed by a parastatal Irrigation Company of the Upper Region (ICOUR).

1.3 Research needs

A number of studies has evaluated the performance of the irrigation schemes in SSA as well as in the UER (Asres, 2016; Djagba et al., 2014; Faulkner et al., 2008; García-Bolaños et al., 2011). However, quantitative evaluations of the irrigation schemes as the whole and with consideration of multiple water users remain scarce. For example, Acheampong et al. (2014) used multiple qualitative indicators to measure the irrigation performance in the Upper East and Upper West regions of Ghana with the main focus on institutional management of small reservoirs, and reported the weak collaboration among stakeholders. Mdemu et al. (2009) and Faulkner et al. (2008) focused primarily on the water demand side, using scheme-level W_p and relative water supply (ratio of the total water supply to the gross irrigation demand) as performance indicators in the UER, and highlighted the problem of over-irrigation and ineffective irrigation scheduling.

Djagba et al. (2014), García-Bolaños et al. (2011) and Poussin et al. (2015) evaluated the field-level crop irrigation only.

Small and Svendsen (1992), in their exposition of various approaches to irrigation performance evaluation, recommended the systems approach where the reservoir-based irrigation scheme is considered as a whole system including the water reservoir, water conveyance and distribution network, the cropping area, as well as the management entity, thereby capturing both the demand and supply sides. Following this approach, Asres (2016) analyzed the water supply and demands of the multi-purpose large-scale Koga reservoir-based irrigation scheme in Ethiopia with the objective of enhancing crop irrigation management in the area of 3,576 ha, and emphasized the need for improving water management to reduce water losses. In the study of four SSA countries including Ghana, Burkina Faso, Zambia and Ethiopia, Venot et al. (2012) found contrasting water demands of multiple users in reservoir-based irrigation schemes and advocated the recognition of the multi-purpose use of their reservoirs besides crop irrigation.

Previous studies have in particular pointed out an inappropriate water use at the field scale in SSA (Asres, 2016; Faulkner et al., 2008) but most research, for example in the UER (Barry and Forkuor, 2010; Mdemu, 2008), focused on assessing the traditional irrigation practice and scheduling rather than developing an improved irrigation schedule for the prevalent cropping systems.

Furthermore, reservoir-based irrigation schemes have traditionally been designed and considered for dry-season crop irrigation alone, in addition to the non-irrigation water uses of the reservoirs. In the wake of increased climate variability reflected in unreliable rainfall patterns and frequent and prolonged dry spells in West Africa (de Bruijn and van Dijk, 2006; Sylla et al., 2016), the potential of these schemes for supplemental irrigation in the rainy season also needs to be explored to capture possible intra- and inter-seasonal variations in the reservoirs' operation and water allocation during both the rainy and dry seasons of cropping. An inter-seasonal consideration appears necessary, because climate and land-use changes create an increasing need to coordinate supplemental irrigation strategies by overcoming dry spells in the rainy season while allowing for water accumulation in the reservoir to fulfill dry-season water demands.

Considering the multi-purpose nature of these irrigation schemes in the face of climate variability, an integrated management of the water demands of the multiple sectors would be helpful in order to improve the reservoir's operation by enhancing equity among water users and secure environmental integrity (Fowe et al., 2015; Venot et al., 2012). To this end, a scenario-based assessment of the performance of the schemes is needed to enable water managers to plan water allocation effectively (Agyenim and Gupta, 2012; Fowe et al., 2015) and to identify the interlinked effects of demand- and supply-management decisions on all users, and thus spot opportunities for synergy and mitigation of water-related conflicts.

Against the backdrop of future food needs, impacts of climate change on water resources, and competing water demands, the research priorities are identified on the one hand for an integrated assessment of the entire system of reservoir-based irrigation schemes, considering the multiple water use sectors and climate variability and, on the other hand, a comprehensive field-scale evaluation of current and potential year-round water use. In particular, revealing the reasons behind the under-performance of irrigation schemes would guide the development of feasible and context-specific solutions to optimize the irrigation water management for food production. This study aimed to assess the performance of irrigation schemes in SSA using the case example of UER in Ghana.

1.4 Research objectives

The research aimed at developing adaptation options to climate variability and increased food demand by improving water management in multi-purpose small- and medium-scale irrigation schemes in the UER under different scenarios of water availability.

The specific objectives include:

i. Assessment of the performance of small- and medium-scale irrigation schemes using systems approach and multiple indicators

ii. Development of improved field-scale irrigation scheduling in the schemes for dry-season crops

iii. Assessment of the potential of the irrigation schemes for supplemental irrigation in the rainy season

iv. Assessment of the entire irrigation schemes considering the multi-purpose water use and climate variability.

1.5 Outline of the thesis

The thesis is organized in seven chapters. Following the introductory Chapter 1, the climatic, geological and hydrological characteristics of the UER are presented and the irrigation schemes selected for the study are described in Chapter 2. Chapter 3 reports on the evaluation of the performance of reservoir-based irrigation schemes by focusing on one medium-scale and one small-scale irrigation scheme. Chapter 4 presents the AquaCrop model-based analysis of suitable irrigation schedules in the study schemes in the dry season. Chapter 5 reports on the potential of small- and medium-scale irrigation schemes for supplemental irrigation in the rainy season. Chapter 6 presents a scenario-based assessment of the irrigation schemes using the Water Evaluation and Planning System (WEAP) model. Finally, Chapter 7 draws overall conclusions based on the study results, outlines limitations of the current study and presents future research needs.

2 STUDY REGION

2.1 Geographical and demographical information

The Upper East region (UER) is located at the north-eastern corner of Ghana between latitudes 10° 30' and 11° 15' North and longitudes 0° and 1° 30' West. It is bordered to the north by Burkina Faso, the east by the Republic of Togo, the west by Sissala East district in Upper West region and the south by West Mamprusi district in the Northern region (Figure 2.1). The total land area of the UER is about 8,842 km^2, which is 3.7% of the total land area of the country (Annor et al., 2009). The region has a population of 1,046,545, comprising 506,405 males and 540,140 females (GSS, 2012) with over 80% engaged in smallholder agriculture as the main source of livelihood (Acheampong et al., 2014; Adwubi et al., 2009; Akomeah et al., 2011). The UER is currently divided into three municipalities and ten districts (Figure 2.1). The main ethnic groups are the Mole-Dagbon, Grusi, Mande-Busanga and Gurma. Among the Mole-Dagbon, the Nabdam, Kusasi, Nankani/Gurense and Builsa dominate.

2.2 Climate and agro-ecological zones

The UER belongs to the Guinea savanna and Sudan savanna agro-ecological zones (AEZs) (Figure 2.2) characterized by a single rainy season starting in April/May and ending in September/October, followed by a dry season from November until April/May (Amekudzi et al., 2015). The mean annual rainfall is about 970 mm (Figure 2.3). The growing period and annual rainfall of the Guinea savanna zone ranges from 180–200 days and 950–1500 mm, respectively. In the Sudan savanna zone, the growing period is in the range of 150–160 days, and annual rainfall ranges between 550 and 900 mm (Amisigo et al., 2015; SRID, 2016). The annual potential evapotranspiration (ET_0) is twice as much as the annual precipitation, but ET is exceeded by rainfall in the rainy season (Mdemu, 2008). Most natural surface waters disappear during the dry season, and years with below-average rainfall and droughts significantly reduce water availability for irrigation, livestock, fishery, domestic uses, and ecology (Mdemu, 2008). Air temperatures are consistently high, with a daily maximum of 40 °C in the hottest month

(March) and 31 °C in the coolest month (August); the mean annual temperature is 29°C (Figure 2.3).

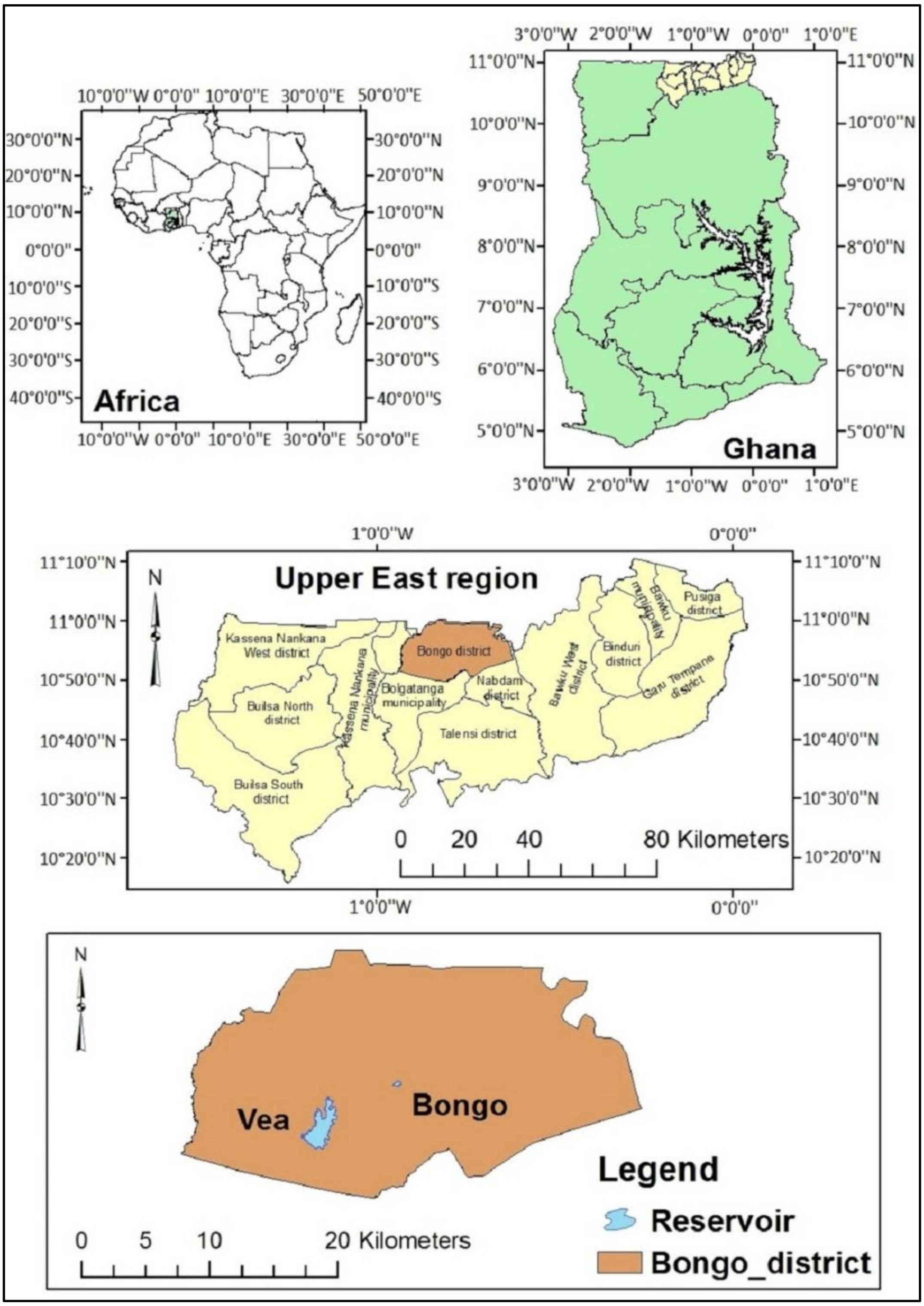

Figure 2.1 Location of the study region and the Vea and Bongo irrigation schemes (Shape files data source: WASCAL database)

Relative humidity fluctuates considerably from < 10% during the dry season (especially in December/January) to > 65% during the rainy season (Sekyi-Annan, 2010) with an annual average of 55% (Adwubi et al., 2009). The region generally experiences low and moderate wind speeds in the range of 0.4–2.5 m s^{-1} (Mdemu, 2008).

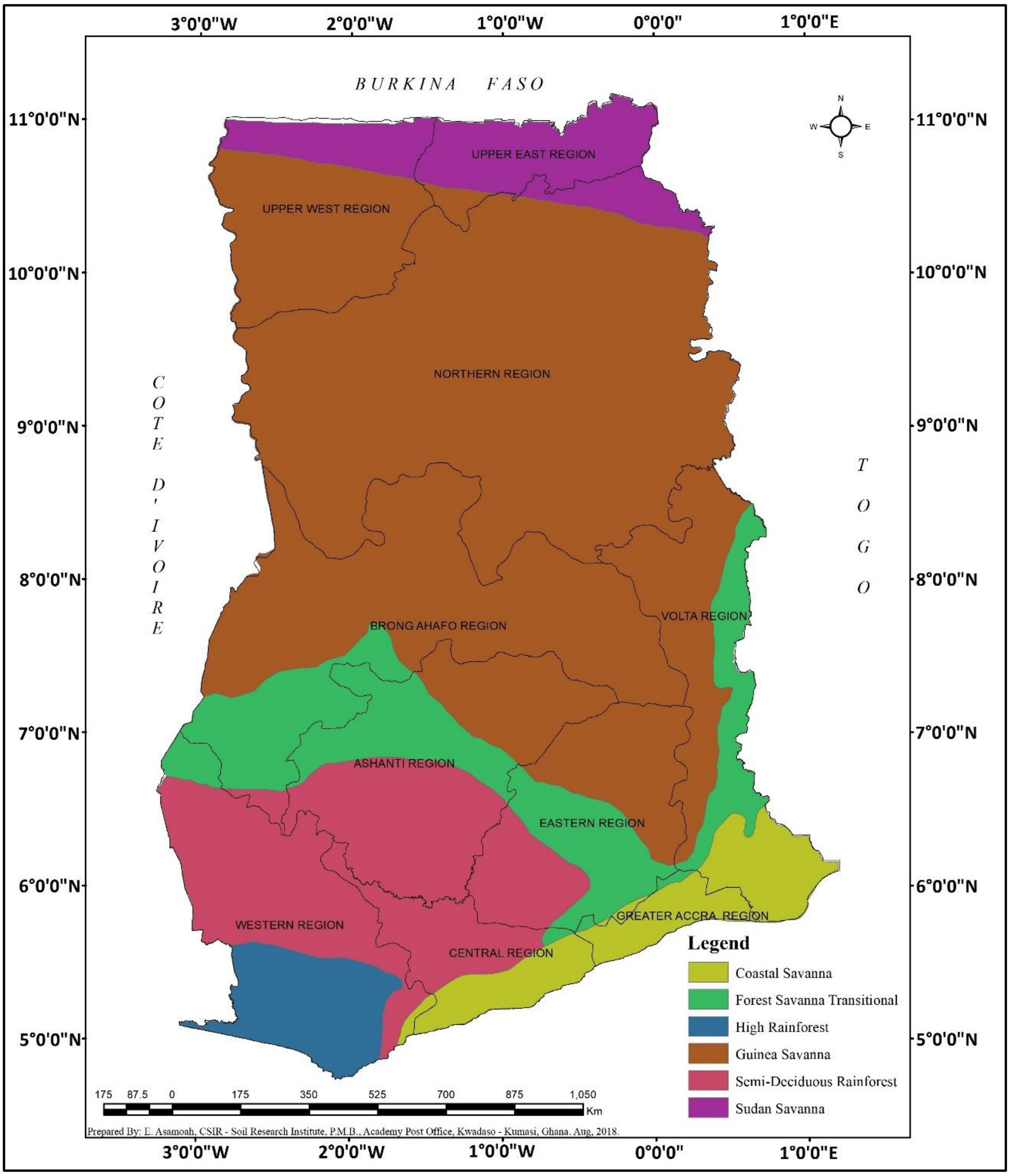

Figure 2.2 Administrative regions and agro-ecological zones in Ghana (Asamoah, 2018)

2.3 Geomorphology, soils, relief and hydrogeology

Granitic, Birimian, and Voltaian rocks are the parent materials (geological formations) in the UER (Adu, 1969; Mdemu, 2008; Ofosu, 2011). Dominant soil types include Gleyic Lixisols, Ferric Lixisols, Haplic Lixisols, Lithic Leptosols, and Eutric Fluvisols located in flood plains and ephemeral streams (Figure 2.4). Soils in the region and large parts of the Sudan savanna zone are characterized by poor fertility influenced by low organic matter accumulation, high temperatures catalyzing the rate of decomposition of organic matter, and excessive burning of vegetation in the dry season (Mdemu, 2008).

The region has a mean elevation of 200 m above sea level (a.s.l.) with gently undulating hills (Adu, 1969; Liebe, 2002; Mdemu, 2008). The ranges of Birimian Greenstone hills with high elevations (457 m a.s.l.) are dominant along the border between Ghana and Burkina Faso in the northern part of Bawku and Zebilla, as well as along the White Volta River to the south-west. Areas of the Bongo and Vea irrigation schemes are characterized by low elevations in the range of 122–260 m a.s.l. with just a few escarpments (518 m a.s.l.) towards the border with Togo (Adu, 1969).

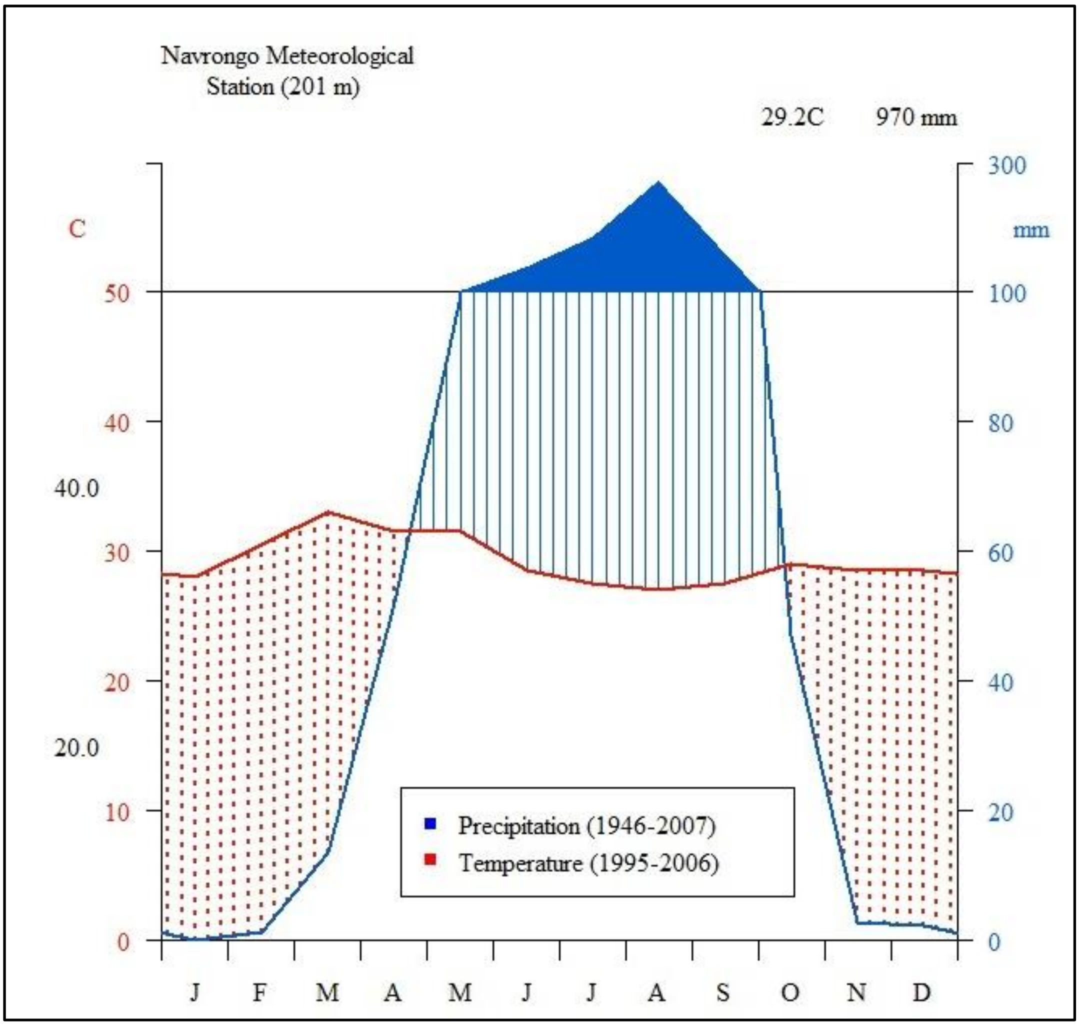

Figure 2.3 Walter-Lieth climate diagram of the Upper East region of Ghana based on data collected at the Navrongo Meteorological station (latitude 10°54’0”N and longitude 1°06’0”W; elevation 201 m a.s.l.). Precipitation data covered the period 1946–2007, and temperature data were measured between 1995 and 2006. Top of graph shows long-term mean annual temperature and rainfall. Value at top-left of temperature axis is mean of the average daily maximum temperature of the hottest month; value at bottom is mean of the average daily minimum temperature of the coldest month. Area shaded in blue indicates the moist period and area shaded in red shows the arid period. Area filled in blue indicates the period of excess water (Sekyi-Annan et al., 2018a).

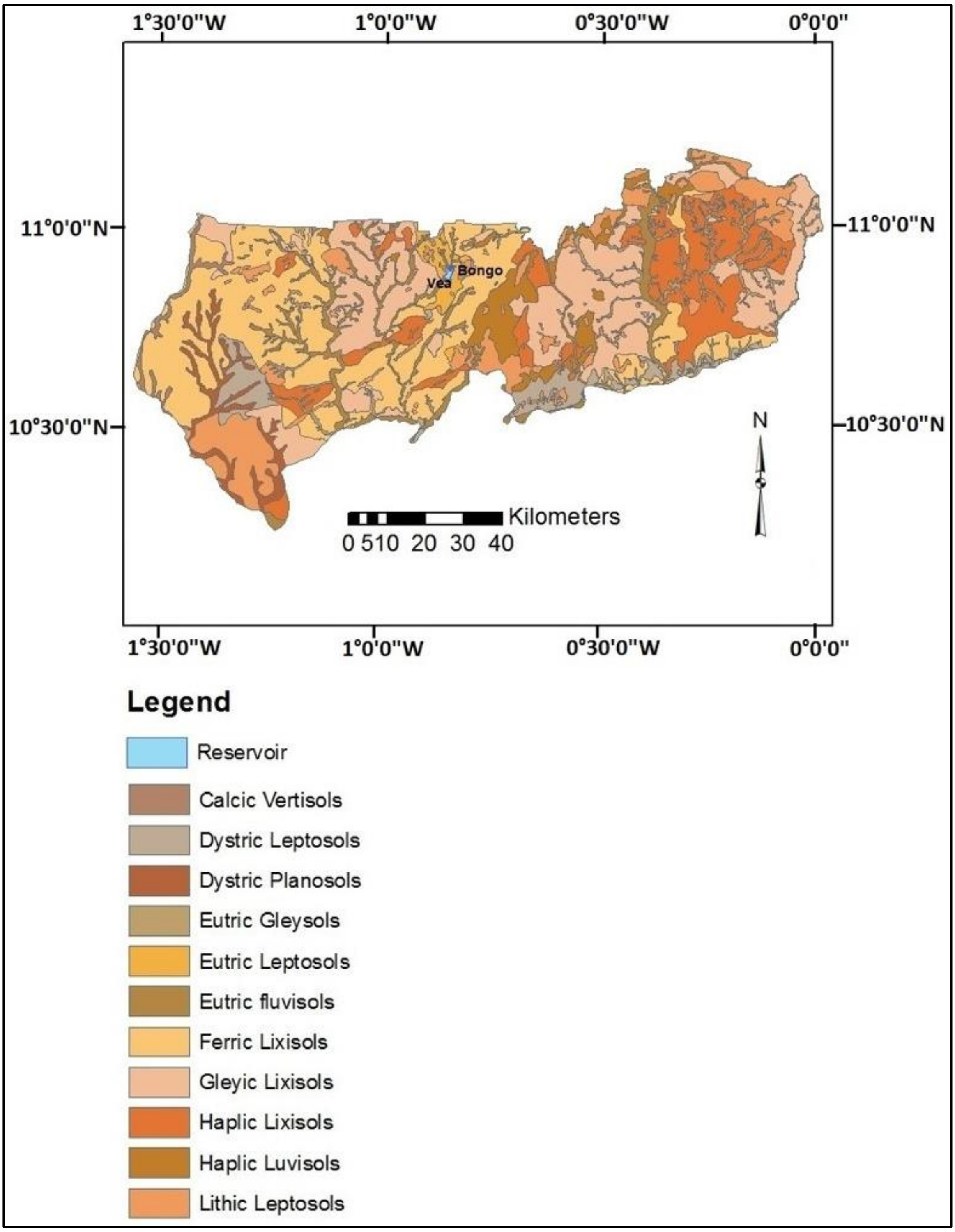

Figure 2.4 Soils in the Upper East region of Ghana (Shape files data source: WASCAL database)

2.4 Vegetation and land use

The dominant vegetation types in the UER are grassland savanna associated with shrubs and trees, and woodland savanna interspersed with perennial grasses in the southern part, and with tussock grasses in the northern part of the region (Mdemu, 2008; Obuobie, 2008). The trees are fire- and drought-resistant (Adwubi et al., 2009). The principal tree species found within the woodland savannah are *Vitellaria paradoxa*, *Adansonia digitata*, *Butyrospermum parkii*, *Daniellia oliveri*, *Tamarindus indica*, *Mitragyna inermis*, *Khaya senegalensis*, *Parkia biglobosa*, *Faidherbia albida*, and *Terminalia macroptera*. The tree species associated with grassland savanna include, *Balanites aegyptiaca*, *Leptadenia pyrotecnia, Anogeissus leiocarpus*, and *Acacia spp*., whereas *Aristida spp.*, *Cenchurus biflorus* and *Schoenfeldia gracilis* constitute the dorminant grass species (Obuobie, 2008).

Rainfed and irrigated agriculture is the main land-use type in the UER. The principal rainfed crops include sorghum (*Sorghum bicolar*), millet (*Pennisetum glaucum*), maize (*Zea mays*), rice (*Oryza sativa*), cowpea (*Vigna unguiculata*), and groundnut (*Arachis hypogaea*). Tomato (*Solanum lycopersicum*), onion (*Allium cepa*), pepper (*Piper longum*), roselle (*Hibiscus sabdariffa*), lettuce (*Latuca sativa*) and rice are cultivated under irrigation (Mdemu, 2008; Obuobie, 2008). Crop farming is commonly combined with rearing of indigenous livestock species including cattle, donkeys, sheep, goats, pigs, and poultry such as chicken, guinea fowl and ducks (Mdemu, 2008; Sekyi-Annan, 2010).

2.5 Hydrology and irrigation systems

The White Volta River drains large parts of the UER southwards through its many tributaries and sub-catchments starting from the northeast along the Ghana-Burkina Faso border through Bawku East and Bawku West (Figure 2.5). The Sissili, Asibilika and Kabia Rivers drain the western side of the region, and the Red Volta River drains the central part of the UER. All the rivers join the White Volta River along the Gambaga escarpment as this flows in the south-west direction into the Northern region of Ghana (Figure 2.5).

The northern part of the UER, comprising the Bongo district and parts of the Kassena Nankana Municipality, is drained by three main sub-catchments including Anayeri, Atankwidi and Yaritanga (Mdemu, 2008; Ofosu, 2011). Both the medium-scale Vea and small-scale Bongo irrigation schemes are located within the Yaritanga sub-catchment of the White Volta Basin. The Tono sub-catchment drains the north-western part of the UER. According to Liebe (2002), tributaries located in the south of the White Volta River in the Gambaga scarp drain away southward from the river.

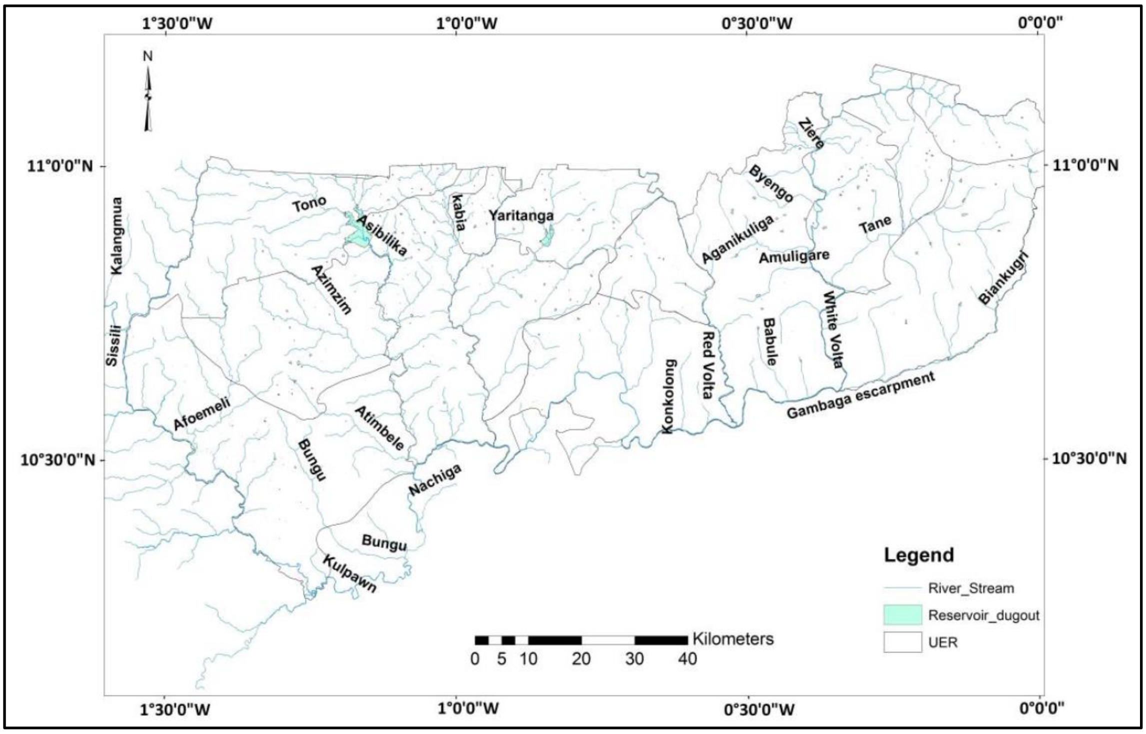

Figure 2.5 Hydrology, small- and medium-scale reservoirs in the Upper East region (Shape files data source: WASCAL database)

The region is dotted with several small- and medium-scale reservoirs located in inland valleys (Figure 2.5). The two medium-scale reservoirs (Tono and Vea) were constructed on streams, whereas the small-scale reservoirs were constructed in valleys to store runoff during the rainy season.

The hydrogeology of the UER is highly variable with low groundwater yield in boreholes ranging between 0.03 and 24.0 $m^3\ h^{-1}$, and a mean borehole yield of 2.1 $m^3\ h^{-1}$ (Ofosu, 2011). According to Obuobie (2008), 8 % of the annual rainfall in the UER recharges groundwater. The main types of aquifers in the UER include fissured zone aquifers and weathered zone aquifers, which could be either confined or semi-confined (Ofosu, 2011).

2.5.1 Vea irrigation scheme

The medium-scale Vea irrigation scheme (VIS) lies between 10° 52′ 02″ N and W 0° 51′ 05″ (Figure 3.2). Its construction started in 1965 and was completed in 1980. The dam is 1,585 m long and has a maximum height of 16 m. The catchment area upstream of the dam is 13,600 ha and the reservoir surface area at the full supply level is estimated at 405 ha. The gross irrigable area is approximately 1,197 ha, yet only 850 ha have been developed for irrigation. However, due to the currently sub-optimal state of the infrastructure, the actual area under irrigation is ≤ 400 ha. The designed storage capacity is 17.27 million m^3 comprising of 16 million m^3 live storage and 1.27 million m^3 dead storage, i.e., the quantity of the water reservoir that is inaccessible for irrigation by gravity flow). The Irrigation Company of the Upper Region (ICOUR) manages the VIS, which provides water for crop irrigation, livestock, fish farming and drinking water needs to Bolgatanga municipality. Rice, tomatoes and leafy vegetables dominate the irrigated cropping systems. Irrigation water supply from the reservoir flows by gravity through two main left and right canals, and diverts into 61 lateral canals, i.e., 31 and 30 along the two main left and right canals, respectively. The left main canal (14.5 km) with a trapezoidal cross-section is out of service due to its poor state. The right main canal is in a relatively good working condition and has a rectangular top section in the lined and upper most reaches (≈ 70 m long from the offtake tank, the first water collection point of the canal; Figure 2.6) with the remaining section (≈ 12 km) of a trapezoidal shape. The methods of on-farm water application are basin irrigation for rice farms, and furrow irrigation coupled with manual water application using a bowl for the other crops. Farms lack drainage facilities.

2.5.2 Bongo irrigation scheme

The small-scale Bongo irrigation scheme (BIS) located between N 10° 54’ 36” and W 0° 47’ 27” was constructed in 1961 (Figure 3.2). It has an embankment length of 625 m and a designed dam height of 6 m. Its catchment area is 98 ha and the estimated reservoir area at the full supply level is 20.7 ha. The actual storage capacity and irrigable area are 0.433 million m^3 and 12.05 ha, respectively. The scheme has a dead storage of 2,600 m^3. It is managed by a community-based WUA and provides water for crop irrigation, livestock and fish farming. There are two main left and right trapezoidal canals that supply water from the reservoir to the farms by gravity flow (Figure 2.6). No lateral canals were constructed. The cropping pattern and irrigation methods are same as in the Vea scheme. Similarly, there are no drains on the farms.

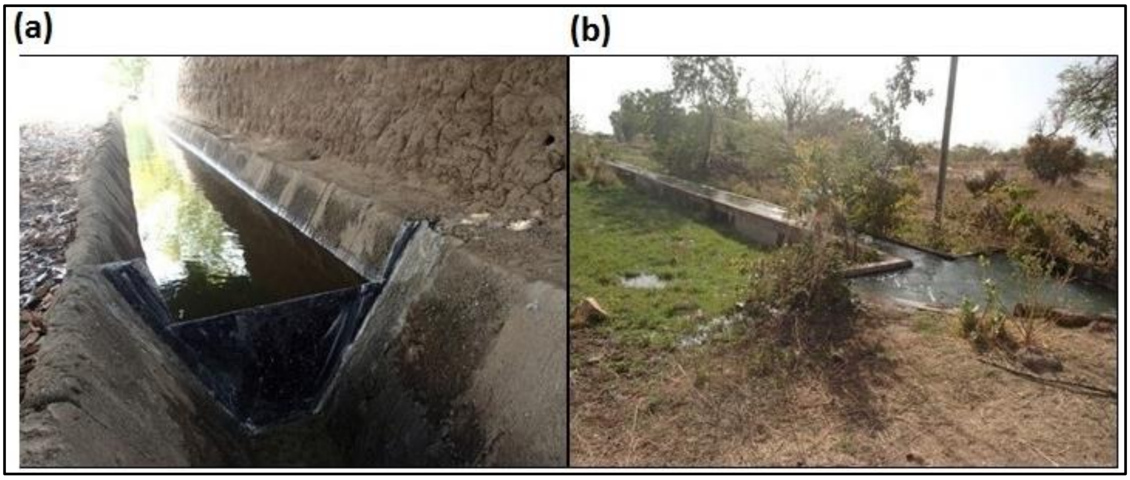

Figure 2.6 Right main canal in the (a) Bongo irrigation scheme and (b) Vea irrigation scheme.

3 PERFORMANCE EVALUATION OF RESERVOIR-BASED IRRIGATION SCHEMES

3.1 Introduction

Agriculture in Sub-Saharan Africa (SSA), primarily practiced by smallholding farmers, faces huge challenges because of increasing water shortages and variability of rainfall due to climate change (Boko et al., 2007; Sylla et al., 2016). Agricultural productivity and incomes will need to double for achieving food security and strengthening the climate change adaptation capacity of the smallholders by 2030 (Barakat et al., 2015; Griggs et al., 2013). Improving irrigation water management is an essential part of the adaptation strategies. In particular, temporal shifts in the rainy season and the occurrence of dry spells can be tackled by introducing supplemental irrigation practices (Fox and Rockström, 2003; Sanfo et al., 2017; Zwart and Bastiaanssen, 2004), whereas improving irrigation scheduling in the dry season can increase crop-water productivity (El Afandi et al., 2010). Field-level soil moisture management in cropping areas, water storage in reservoirs to ensure year-round water availability (Droogers and Aerts, 2005; Pereira et al., 2002; Rockström and Barron, 2007), and an integrated management of multi-purpose reservoirs (Venot et al., 2012) are also considered for coping with the impact of climate change and variability in SSA.

At present, more than 50% of the population of SSA relies on rainfed farming as the main source of livelihood (You et al., 2011). Nevertheless, over 19,000 reservoir-based irrigation schemes have been constructed in most of SSA, with more than 1,000 small- and medium-scale schemes in Ghana, West Africa (Mutambara et al., 2016; Pereira et al., 2012; Venot et al., 2012; You et al., 2011). Of these, 220 schemes are located in the UER (Adwubi et al., 2009; Venot et al., 2012). In the UER, the reservoir-based irrigation schemes provide water for crop irrigation in the dry season and for other competing users including livestock, fishery and households throughout the year (Acheampong et al., 2014; Faulkner et al., 2008). The adequacy of the performance of these irrigation schemes is increasingly challenged due to changing climate and land use, population growth, and competing demands, besides the basic need for rehabilitation of the systems installed mostly in the 1960s and 1970s (Acheampong et al., 2014; Berhane et al., 2016; Mutambara et al., 2016; Venot et al., 2012).

Although the performance of the irrigation schemes in SSA and also in the UER have already been investigated, quantitative evaluations of the irrigation schemes as a whole and with consideration of multiple water users are rare. For example, Acheampong et al. (2014) used multiple qualitative indicators to measure performance in the Upper East and Upper West regions of Ghana with the main focus on institutional management of small reservoirs. Mdemu (2008) and Faulkner et al. (2008) focused primarily on the water demand side, using scheme-level water productivity and relative water supply as performance indicators in the UER. Djagba et al. (2014), García-Bolaños et al. (2011) and Poussin et al. (2015) evaluated the field-level crop irrigation only.

Small and Svendsen (1992) recommended the systems approach to irrigation performance assessment where all the components of a reservoir-based irrigation scheme including the water reservoir, water conveyance and distribution network, and the cropping area as well as the management entity are evaluated in order to capture both the demand and supply sides of the scheme as the whole. In accordance with the aforementioned approach, Asres (2016) analyzed both the water supply and demand of the multi-purpose, large-scale reservoir-based Koga irrigation scheme in Ethiopia with the objective of enhancing crop irrigation management in the area of 3,576 ha. Furthermore, in the study of the four SSA countries including Ghana, Burkina Faso, Zambia and Ethiopia, Venot et al. (2012) found contrasting water demands of multiple users in reservoir-based irrigation schemes and advocated the recognition of the multi-purpose use of their reservoirs besides crop irrigation.

Such an integrative approach for the assessment of irrigation schemes in SSA requires a combination of suitable indicators (Ali, 2011; Bos et al., 2005; Pereira et al., 2012). In particular, the *water availability index* provides information about whether water availability is adequate to meet the total water demand of the scheme (Xu and Wu, 2017). *Water conveyance network efficiency*, *field application efficiency* and *overall system efficiency* measure the technical performance of the water delivery subsystem and water utilization at field-level (Bos et al., 2005). The adequacy of the crop irrigation scheduling can be evaluated through *crop water productivity* (El Afandi et al., 2010), whereas *relative transpiration* specifies the crop-water status and enables an assessment of appropriateness of irrigation. Lastly, the *delivery performance ratio* (Bos et al., 2005) is useful to assess the ability of the management entity to comply with an irrigation schedule.

This chapter presents the assessment of the performance of irrigation schemes in SSA based on the integrated systems approach and considering competing water uses of the reservoirs. In particular, the assessment focused on the case of small- and medium-scale reservoir-based irrigation schemes in the UER of Ghana with the aim to reveal priority components within the systems for the irrigation performance improvement. To this end, assessed were (i) the current storage capacity of the reservoirs for the overall scheme operations, (ii) the efficiency of the conveyance and distribution networks in transporting water from the off-take tank to the field inlet, and (iii) the efficiency of the water use at the field level.

3.2 Materials and methods

3.2.1 Study sites

The study area in the UER of Ghana was chosen because it is typical for the operations of reservoir-based irrigation schemes. The selected medium- and small-scale schemes, i.e., the VIS and the BIS located in the Bongo district of the UER, also represent the typical spectrum of reservoir-based irrigation schemes in the region. Besides differences in size, these irrigation schemes were selected due to their different management modes (Vea is managed by the ICOUR and Bongo by a WUA), and because of their accessibility for the research. In the Vea reservoir, there is usually a considerable amount of water remaining at the end of the dry season owing to underutilization of the water resources.

The cultivated area per farmer in the study area is in the range of 0.01–0.10 ha in the dry season, with the common practice of tomato (*Solanum lycopersicum*) and rice (*Oryza sativa*) monocropping, and leafy vegetables including roselle (*Hibiscus sabdariffa*), lettuce (*Lactuca sativa*), and cowpea (*Vigna unguiculata*) intercropping. However, roselle was monocropped in the VIS. Leafy vegetables are cultivated 2–3 times in the dry season owing to their relatively short growing cycle. Irrigation water from the reservoir is conveyed through canals to the fields by gravity. Water is diverted into furrows and applied to the fields manually using a bowl. The number of irrigation events for the cultivation of tomato was 20–29, for leafy vegetables 11–23, and for rice 10. The irrigation interval was 7–8 days for rice and 2–5 days for the other crops. Rice farmers watered their fields weekly, thereby subjecting the crop to alternating wet and dry conditions. During the observation period, the mean groundwater table was in the range of 0.6–1.3 m and 0.7–2.8 m below the ground surface in the BIS and VIS, respectively.

The observations were conducted in the rainy and dry seasons from May 2014 to April 2016. This chapter presents the results for the dry seasons when most water for irrigation is needed. Twelve farming fields were surveyed to capture spatial variations in water use. The map, elevation-area and elevation-capacity curves of the VIS were collected from the ICOUR through personal communication. Furthermore, the map of the BIS and the inventory of dams in the UER were collected from the Ghana Irrigation Development Authority also through personal communication. Next, informal group discussions with farmers, consultants, and agricultural extension officers were conducted to support the appropriate selection of cropping fields for monitoring. Data collection covered all components of the scheme including water reservoir, water conveyance network, and cropping area as well as the management entity. Suitable performance indicators were selected for each component (Figure 3.1).

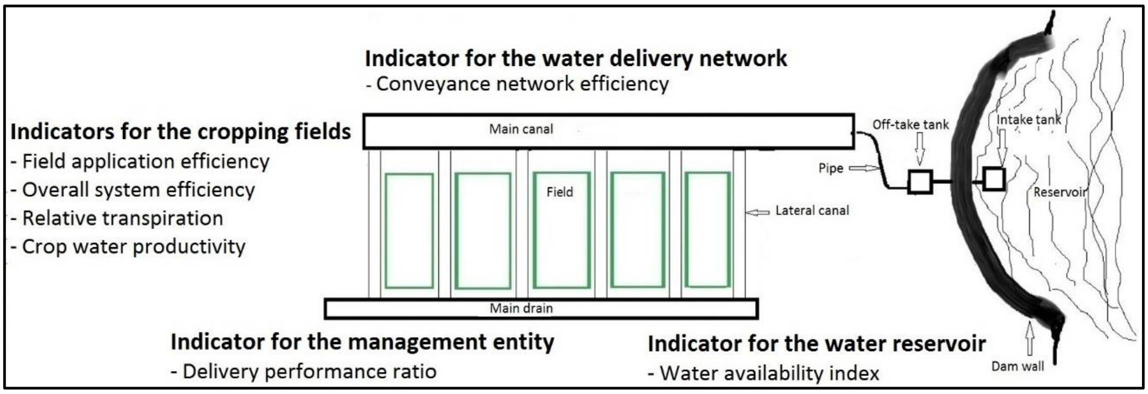

Figure 3.1 Schematic representation of the reservoir-based irrigation schemes and indicators for their performance evaluation in the UER of Ghana

3.2.2 Selection of farmers' fields

The fields were selected to represent the top, middle, and tail sections of the irrigable area in order to cover the range of water-accessibility conditions. In the VIS, two fields were selected in the top section and four fields in the middle section giving a total of 6 sites (Figure 3.2). No field was selected in the tail section of the VIS because groundnut and soybean were cultivated there, and these cropping systems differ significantly from the typical farming practice in the scheme. All selected fields were fed by the right main canal (mostly through two lateral canals) since the left main canal was seriously deteriorated. In the BIS, one field in the top section, four fields in the middle section (including two fields along the right and the left canals), and one field in the tail section were selected (Figure 3.2). Other criteria for selecting these fields were their cultivation in both the rainy and the dry seasons and availability of suitable locations for the discharge measurements in the dry season. However, during the study period, the tail-end field in the BIS was only cropped in the rainy season with rice. The main dry-season crops covered in this study were tomato, leafy vegetables and rice. Measurements were conducted at two fields in each cropping system per scheme as described in Chapters 4 and 5. Due to water scarcity caused by malfunctioning infrastructure in the VIS, the rice farmers (VF2 and BNF2 fields) could not farm in the 2015–2016 dry season.

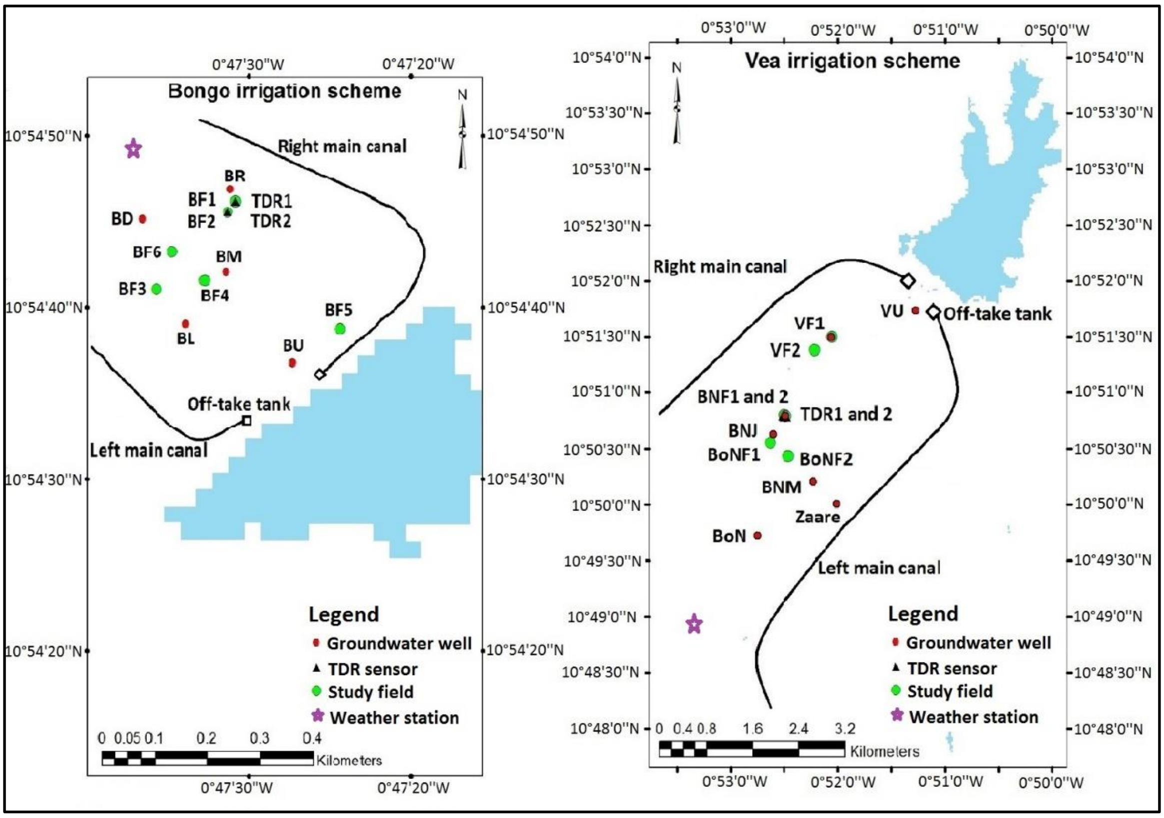

Figure 3.2 Location of irrigation schemes and study sites. BF1–6 = Bongo fields, BNF1, 2 = Bongo Nyariga fields, BoNF1, 2 = Bolga Nyariga fields, BR = Bongo right well, BL = Bongo left well, BM = Bongo mid-slope well, BD = Bongo downslope well, BU = Bongo upslope well, VF1, 2 = Vea fields, VU = Vea upslope well, BNM = Bongo Nyariga middle well, BNJ = Bongo Nyariga junction well, TDR1, 2 = Time domain reflectometers.

3.2.3 Soil profile characteristics

A soil profile description was conducted at the study sites to ascertain the soil types and their physico-chemical characteristics, and to understand their effect on irrigation performance at field level. In addition, soil information was required particularly for developing irrigation schedules. To this end, three soil profile pits were dug (at BF1 and BF4 in the BIS and at BNF2 in the VIS) to depths of 1.2–1.3 m in the Akrubu and Yaratanga soil series identified in the irrigation schemes. Soil samples were collected from the morphological soil horizons and analyzed in the soil laboratory at the Soil Research Institute in Kumasi, Ghana (Appendices 9.1–9.4).

The soil chemical properties, bulk density, soil moisture at saturation, field capacity, and permanent wilting point were determined in the laboratory (Mbah, 2012) (Appendices 9.5–9.7). Soil pH (1:1) was determined with a glass electrode pH-meter, which was standardised with two aqueous solutions of pH 4 and 7. Total nitrogen (N) was determined by the Kjeldahl method. The wet combustion method of Walkley and Black (Schulte, 1995) was employed to analyse organic carbon and subsequently the organic matter content was calculated. Available phosphate (P) was analyzed using Bray-1 solution, and the ammonium acetate (NH_4OAc) pH 7.0 method was applied to determine cation exchange capacity (CEC). Concentrations of magnesium (Mg) and calcium (Ca) were determined using the atomic absorption spectrophotometer, while concentrations of sodium (Na) and potassium (K) were measured with the flame photometer.

Saturated hydraulic conductivity (K_{sat}) was determined in the laboratory by the falling head method (Pedescoll et al., 2011) using undisturbed soil cores from the three soil pits. Comparison of the measured K_{sat} values with those determined from the pedo-transfer function based on soil texture and organic matter content (Raes et al., 2012a; Saxton and Rawls, 2006) revealed significantly lower values than the laboratory measured. This was likely caused by incomplete saturation of the undisturbed soil samples (especially samples with high clay content) before the test, leakage along the metal cylinder during the test, and the impact of soil structure and macropores. Consequently, the K_{sat} values estimated from the pedo-transfer functions were used in the study. Infiltration rate was determined in situ with the double ring infiltrometer (Touma and Albergel, 1992) at six locations (two locations for each of the fields).

The soil types identified using the local soil series system and classified according to World Reference Base for Soil Resources (FAO, 2014) revealed similar soil types in both Bongo and Vea irrigation schemes. In particular, Gleyic Arenosols and Calcic Gleysols were found in the BIS cropping fields, and Calcic Gleysols in the VIS fields. These soils were characterized by pH > 7, shallowness (0–40 cm) of rooting zone, low organic matter and N contents, and low infiltration capacity.

3.2.4 Actual storage of the reservoirs

Vea irrigation scheme

A water-level logger (TD-DIVER) was installed on April 22, 2014, near the dam in the reservoir for continuous recording of water levels at 10-min intervals as information for calculating daily means. Using these water-level data coupled with a capacity-elevation curve, reservoir storage capacity and time-dependent storage were determined. The following equation, which relates reservoir storage (V, m^3) with water elevation (E, m), was derived from the capacity-elevation curve:

$$V = (0.1801\,E^2 - 64.5258\,E + 5780.2299) \times 10^6 \qquad (3.1)$$

Bongo irrigation scheme

A geodetic survey was conducted on September 12, 2014, to establish the elevation-area-capacity curves for the Bongo reservoir. Six staff gauges, each with 100-cm-metric graduations, were installed along a straight line in the reservoir starting from the deepest location towards the spillway of the dam. The maximum depth of the reservoir was 5.5 m. Daily monitoring of the water level from installed staff gauges and elevation-area-capacity curves were used to determine storage capacity and time-dependent volume of the reservoir. Considering the nearly half-square pyramidal shape of the Bongo reservoir (Liebe, 2002), the flooded area (A, m^2) was first determined from the water elevation and storage was calculated as follows:

$$V = 0.0154A^{1.3995} \qquad (3.2)$$

where

$$A = (0.5495\ E^2 - 246.9193\ E + 27737) \times 10^4 \qquad (3.3)$$

The plausibility of this approach was determined by comparing the above storage capacity equation (Eq. 3.3), which is specific for the Bongo reservoir, with a generic storage capacity equation ($V = 0.00857A^{1.4367}$) derived for small-scale reservoirs in the UER by Liebe et al. (2005). Because the cropping season in 2014–2015 began before the establishment of the elevation-area-capacity curves for the Bongo reservoir on December 10, 2014, reservoir storage had to be estimated.

3.2.5 Gross water demand for multiple users

Gross irrigation water input

A 100-cm metallic staff gauge was installed onto the left levee in the direction of flow of the lined rectangular section of the right main canal in the VIS to determine discharge representing water supply from the off-take tank. Discharge was estimated using Manning's equation for open channels (Vatankhah, 2015) and applying the mean value of roughness coefficient for concrete-lined channels with trowel finish in the range of 0.011–0.015 (Chow, 1959). A measuring weir could not be used in Vea due to the height of the levee and potential reduction of flow velocity. In the BIS, a 50-cm staff gauge and a Cipolletti weir (Boiten, 1993) were installed in both the left and right lined trapezoidal canals during the 2014–2015 dry season. In the following dry season, the Cipolletti weirs were removed but Manning's equation was used to determine discharge. The duration of water supply was recorded and multiplied by discharge to calculate gross water supply to the scheme.

A discharge equation for flows through pipes installed at the field's inlet during irrigation events was developed from in-situ measurements. To this end, the time required to fill a bucket of known volume was recorded following the "volumetric approach" for seven different water depths read from the staff gauge in the canal. Discharges corresponding to the seven measured water depths were computed, and subsequently discharge (Q, $m^3 s^{-1}$) was related to water depth (h, m) as shown in Eq. 3.4. The R^2 and standard error of Eq. 3.4 are 0.972 and 0.001, respectively.

$$Q = 0.073h^{1.334} \tag{3.4}$$

where h is depth of water (m) in the canal at the farm inlet.

$$Q\ (Manning's) = A\frac{1}{n}R^{2/3}S^{1/2} \tag{3.5}$$

where *A* is cross-sectional area of canal in m², *n* is Manning roughness coefficient, *R* is hydraulic radius in m and *S* is slope of canal bed; the water level slope was approximated by the longitudinal slope of the canal bottom.

$$Q\ (Cipoletti\ weir) = 1.859bh^{3/2} \tag{3.6}$$

where *b* is length of crest in m and *h* is height of water level above crest in m.

In the VF1 field, where a pump was used to obtain water from the right main canal, actual discharge of the pump was determined using the volumetric approach. Because discharge varied during an irrigation event, the event was split into sub-periods of constant discharge. The gross irrigation amount (GIA) per event was determined by summing up sub-discharges multiplied by the duration of the respective sub-periods. The GIA for each crop per field during the entire dry season was subsequently calculated.

The GIA of the scheme at field level was computed based on the respective shares of irrigable area cultivated with the principal crops. In the VIS, the shares of the irrigable area were 37% (rice), 48% (tomato), and 12% (leafy vegetables). In the BIS, these shares were 5%, 40%, and 55% for the same crops, respectively.

Livestock water demand

Data on livestock population of different species in the Gowrie and Bongo Central sub-districts for the VIS and the BIS, respectively, were collected from Bongo district office of the Ministry of Food and Agriculture (MOFA, 2013–2016) of Ghana (Appendix 9.8). The livestock water requirement was determined according to Peden et al. (2003). The livestock water demand during the 2014–2015 dry season was more than that in the

2015–2016 dry season because the former had a longer dry period than the latter (7 vs. 5 months). During rainy seasons, the livestock largely depended on rainwater, which collected in the neighborhood ponds rather than on reservoir water.

The daily water intakes for different livestock species under dry and hot tropical conditions (Table 3.1) were calculated as follows:

$$LWD = \sum_{i=1}^{n} P_i \; DWI_i \; TLU_i \tag{3.7}$$

where LWD is the livestock water demand (m³ day⁻¹), *n* is number of different species of livestock, *P* is livestock population per species, DWI is daily water intake (m³) per tropical livestock unit (TLU), in which 1 TLU = 250 kg live weight.

Table 3.1 Estimated livestock daily water intake under Sahelian conditions

Species	Tropical Livestock Unit (TLU)	Mean liveweight (kg)	Daily water uptake (m^3 TLU^{-1} day^{-1})	
			Wet season	Dry season
Cattle	0.7	180	0.0143	0.0386
Donkeys	0.4	105	0.0125	0.04
Sheep	0.1	25	0.02	0.05
Goats	0.1	25	0.02	0.05

Source: Adapted from Peden et al. (2003). TLU = tropical livestock unit

Fishery water demand

In the VIS, 22 fish ponds were fed by the reservoir. Data on the dimensions of the ponds were collected from the fisheries department of MOFA (Appendix 9.9). In the BIS, where fish farming was practiced directly in the reservoir, dead storage was assumed to cover the fishery water requirement.

Drinking water demand

Data on water withdrawals from the Vea reservoir were collected from the Ghana Water Company Limited (GWCL), and year-round drinking water demand in the VIS was computed from monthly water withdrawals during May 2014 through April 2016 (Appendix 9.10). The Bongo reservoir was not used to cater for drinking water needs as these were satisfied via groundwater boreholes. However, large withdrawals were recorded in 2014–2015 due to road constructions in Bongo township. Although urban construction was not a regular user of the reservoirs' water, contractors were able to satisfy the occasional water needs for road construction after obtaining permission from the local authorities. This aspect was, however, not considered in the current study.

3.2.6 Water availability index

The Water Availability Index (WAI) indicates a reservoir's capability of meeting the total water demand of the scheme (Eq. 3.8), and it assists in analysing whether insufficient water availability is caused by low water storage or by internal factors within the irrigation system such as percolation and seepage losses along the canals and poor irrigation practices at the field level. It therefore indicates the potential of the scheme to provide water for supplemental irrigation during dry spells in the rainy season.

$$\text{WAI} = \frac{\text{Total water supply available to scheme}}{\text{Total scheme water demand}} \tag{3.8}$$

Reservoir storage, including dead storage, at the beginning of the dry season was taken as total water supply available to the BIS. For the VIS, the storage at the beginning of the rainy season (May 21, 2014) was used owing to the year-round water abstractions by the GWCL. The total water use of the schemes was determined by adding the gross amounts of multiple water uses.

3.2.7 Efficiency of water delivery and field application

Conveyance network efficiency

The ponding method (Ali, 2011; Leigh and Fipps, 2004), wherein two ends of the canal section were blocked with sandbags and clay to create a stagnant pool of water and the reduction in water level monitored over 24 h, was applied for the estimation of percolation and seepage loss rates of irrigation water flowing from the off-take tank at operational level to the tail end of the canal. The condition of the canal reach was not uniform, and therefore canal sections of considerable lengths and considered as representative of the existing condition were selected for the ponding test, i.e., 358 m (right canal) and 347 m (left canal) in the BIS, and 325 m of a lateral canal in the VIS. Evaporation loss from the canal was not considered as it was numerically small in relation to seepage and percolation losses (as indicated by estimations based on ET_0 = 5.9 mm day^{-1} and the water surface of the canal). The percolation and seepage losses (S_l, m^3 s^{-1}) along the total canal reach were determined as follows:

$$S_l = P \ L \ S_r \tag{3.9}$$

where *P* is wetted perimeter (m), *L* is total length of canal (m), and S_r is average seepage loss rate (m^3 m^{-2} s^{-1}).

The conveyance network efficiency (E_n, %) was subsequently determined as follows:

$$E_n = \frac{(\mathrm{Q_i} - \mathrm{S_l})}{\mathrm{Q_i}} * 100\% \tag{3.10}$$

where Q_i is the discharge at inlet.

E_n indicates the share of water delivery from the off-take tank that reaches the field inlet. The E_n was further determined for each cropping field (E_{nf}) by considering the length of the canal section from the off-take tank to the field inlet to assess the overall system efficiency at field level depending on the location of the field along the canal.

Field application efficiency

The net irrigation requirement (NIR, mm) per irrigation event during the 2014–2015 dry season was estimated from the actual ET and consideration of the capillary rise (Steduto et al., 2012). In the following dry season, time domain reflectometry (TDR CS655) sensors were installed and the NIR was estimated from the soil moisture change before and after irrigation, with field capacity as upper limit. The sensors were installed in two fields per irrigation scheme at four soil horizons (Figure 3.2). In the BIS, TDR1 set was installed at 0.1, 0.36, 0.56, and 0.72 m, and TDR2 at 0.1, 0.33, 0.52, and 0.64 m. In the VIS, TDR1 set was positioned at 0.1, 0.23, 0.47, and 0.61 m, and TDR 2 at 0.10, 0.22, 0.46, and 0.70 m. In the VIS, soil moisture time-series in the BNF1 and BNF2 fields were not collected in 2015–2016 because the data logger was stolen. Furthermore, the TDR sensors installed in deeper horizons (0.4–08 m) in the BNF1 field malfunctioned in 2014–2015, thus preventing measurements. Groundwater wells were installed in the same fields and across schemes with depths from 2–4.9 m and 2.7–5.5 m in the BIS and the VIS, respectively (Figure 3.2), to monitor shallow groundwater levels for the estimation of the capillary rise to the root zone. Field application efficiency (E_a, %) per event was determined as follows:

$$E_a = \frac{\sum_i^n \frac{NIR}{GIA} 100\%}{\mathrm{n}} \tag{3.11}$$

where n is the number of irrigation events.

E_a estimates the share of water delivered that actually compensates the root-zone deficit and indicates losses due to evaporation, runoff from the field, and percolation below the root zone (Ali, 2011). In 2014–2015, E_a could not be determined for BF5 rice field in the BIS and for all VIS fields, except for tomato VF1 field, owing to agronomic challenges and diseased/perished crops.

Overall system efficiency

The overall system efficiency (E_s, %) expresses the share of water supply to the entire scheme that is put to beneficial use by the crops:

$$E_s = E_{nf} E_a \quad (3.12)$$

Thus, E_s measures the degree to which irrigation water supply meets the NIR at the scheme level. However, additional water losses (e.g., evaporation) were assumed numerically negligible in the E_s calculations (Bos and Nugteren, 1990).

Delivery performance ratio

In the absence of canal flow-measuring devices in the VIS and the BIS, the delivery performance ratio was adapted by substituting the flow rate of irrigation water by the duration of flow. This indicator shows the ability of the management entity to comply with the intended irrigation schedule and was determined as follows:

$$\text{Delivery performance ratio} = \frac{\text{Actual duration of water supply}}{\text{Intended duration of water supply}} \quad (3.13)$$

3.2.8 Determination of water productivity and relative transpiration

Water productivity

A harvest area was demarcated within each of the selected fields. For row crops, two 8-m long rows were defined for yield determination, whereas for rice fields, 8-m² areas were defined (Bell and Fischer, 1994). Plants within this area were harvested at the end of the cropping season, and the total aboveground biomass for each crop was weighed. The crop yield components (rice grains, tomato fruits, and vegetable leaves) were weighed separately. The samples were oven-dried at 70–90 °C to constant weight for at least 72 h to determine the dry matter (Bell and Fischer, 1994). However, the fresh weights of tomato and leafy vegetables were used in the computation of the crop water productivity, W_p, (kg m^{-3}), as these yield components are sold fresh. The dry season W_p was calculated as follows:

$$W_p = \frac{\text{Crop yield}}{\text{GIA}} \tag{3.14}$$

This indicator enabled assessment as to whether water was utilized productively. This assessment was restricted to tomato (BNF1) and leafy vegetable (BNF2) fields in the VIS, because the early onset of the rainy season in 2016 caused waterlogging which, due to the absence of drainage structures, led to failed yields. Therefore, crop yield estimations were instead conducted in neighboring fields of similar soil conditions and farming practices.

Relative transpiration

The FAO AquaCrop model, which was parameterized and validated with field data (Chapter 4) was used to determine the daily actual (T_a) and potential transpiration (T_p) that enabled the calculation of the relative transpiration (T_r) of each crop over the crop cycle (Eq. 3.15). The data required by the AquaCrop model include climate (daily minimum and maximum temperature, solar radiation, relative humidity, wind speed, daily rainfall), crop characteristics (planting and harvesting dates, plant density, maximum rooting depth, maximum canopy cover, crop yield, aboveground biomass, harvest index), soil profile characteristics (texture, soil moisture at saturation, field capacity and wilting point, saturated hydraulic conductivity, initial soil fertility, depth to soil layer restrictive to root penetration, and fertilization), and irrigation and soil water data (method of field-level water application, actual irrigation dates, GIA, soil moisture data). When T_r is <1.0, there may be water stress because of soil moisture dropping below the allowable depletion limit or aeration stress as a result of over-irrigation. Either type of stress leads to crop yield loss. Therefore, T_r indicates the appropriateness of irrigation practices and is calculated as follows:

$$T_r = \frac{T_a}{T_p} \quad (3.15)$$

The crop T_r in the VIS could be determined only for tomato (VF1 field) in 2014–2015, and for tomato (BNF1 field) and leafy vegetables (BNF2 field) in 2015–2016, because of the failed yields in the other cropping fields. For the same reason, T_r of rice at BF5 field could not be determined in 2014–2015.

3.3 Results

3.3.1 Reservoir performance

Water supply to the VIS and gross water demands of multiple users indicated that only 36–38% of the available reservoir water was used during the two observation seasons (Table 3.2). In the BIS, the 2014–2015 dry season recorded a 30% deficit in water supply while about 70% of the available water was used in the following dry season (Table 3.2). The low storage of 0.076 million m³ in 2014–2015 further declined to dead storage water level in February 2015 largely due to urban construction needs during the study period. This reduced the water supply for crop irrigation towards the end of the 2014–2015 dry season.

3.3.2 Performance of the water conveyance network

The comparison of the conveyance network efficiencies with the target value of 95% for concrete lined canals (Bos et al., 2005) indicates that only the Bongo right canal in the small-scale BIS was highly efficient (99%). Considering the relatively good condition of the measured section of this canal, the value of E_n is not representative of the whole network because severe deterioration affected about 328 m of the length of the canal. Hence, although high conveyance efficiencies are achievable, the current efficiency in the deteriorated sections is low. The Bongo left canal in the BIS gave a somewhat lower conveyance efficiency of 90% (Table 3.3). The measured lateral canal in the medium-scale VIS showed an intermediate efficiency value of 91%.

Table 3.2 Water availability index (WAI) and the gross water use for multiple users of the Vea and Bongo irrigation schemes for two dry seasons

	Vea irrigation scheme		**Bongo irrigation scheme**	
Water use (million m^3)	2014–2015	2015–2016	2014–2015	2015–2016
Initial storage	**11.05**	**13.72**	**0.076**	**0.286**
Domestic water withdrawal	2.103	2.074	–	–
Crop irrigation amount	1.99	2.7312	0.0753	0.1891
Livestock demand	0.0521	0.0373	0.0259	0.0214
Fishery water use	0.0954	0.0954	0.0026	0.0026
Gross water use	**4.24**	**4.939**	**0.1037**	**0.2131**
WAI	**2.6**	**2.8**	**0.7**	**1.3**

Table 3.3 Dimensions and network efficiencies of conveyance canals in the Vea and Bongo irrigation schemes.

Parameter	Vea lateral canal	Bongo right canal	Bongo left canal
Top width (m)	0.9	0.75	0.7
Bottom width (m)	0.34	0.3	0.28
Total length (m)	1000	570	600
Operational water depth (m)	0.2	0.37	0.37
Initial discharge at canal head ($m^3\ s^{-1}$)	0.14	0.39	0.28
Seepage and percolation loss rate ($m^3\ m^{-2}\ s^{-1}$)	1.6155×10^{-5}	6.3013×10^{-6}	4.3466×10^{-5}
Seepage and percolation loss ($m^3\ s^{-1}$)	0.0125	0.0041	0.029
Network efficiency (%)	**91**	**99**	**90**

3.3.3 Soil moisture dynamics and field application efficiency

The reduced irrigation supply in the BIS in 2014–2015 (Table 3.2) was reflected in the relatively sporadic and lower irrigation applications, particularly in the tomato field where lowest root-zone soil moisture content (SMC) was observed (Figure 3.3a). Otherwise, because of over-irrigation and capillary rise (Table 3.4), SMC in the sub-horizons (0.2–0.8 m) of the cropping fields was commonly above field capacity (Figure 3.3) ranging between 14.7 and 18 Vol-% in the BIS. In the following season, the tomato field was frequently irrigated with higher GIA per event, and consequently exhibited much higher SMC in the root zone (0.37 m) and higher variations in soil water that significantly declined towards the end of the cropping season (Figure 3.3b). In the leafy vegetables field, only the root-zone (0–0.2 m) showed SMC variations along with a midseason decline in 2014–2015 (Figure 3.3c). Such midseason decline was also observed in the following year, which was characterized by more frequent and larger water applications, resulting in considerable SMC variations (Figure 3.3d).

As in the BIS, sub-soil SMC in the medium-scale VIS was constantly found above field capacity, which measured between 22 and 38.9%. The topsoil showed generally lower and much variable SMC as the crop-water uptake was highest in the uppermost part of the root-zone and due to the relatively high infiltration rate (226 mm h^{-1}). Because of frequent and ample water applications, the root-zone SMC in both VIS fields was observed to be near field capacity (about 20%), except in the tomato field that showed a prolonged decline in soil water during the middle of the 2014–2015 season caused by the interrupted water supply. This interruption resulted from the poor condition of the lateral canal that fed the tomato field in the VIS, coupled with the high ET (up to 7.9 mm day^{-1}) observed in this period (Figures 3.3e, f).

The field application efficiency (E_a) ranged more widely from 25–68% in the small-scale scheme with an average of 46% across the dry seasons than in the medium-scale scheme (52–58%) where it averaged 56% (Table 3.4).

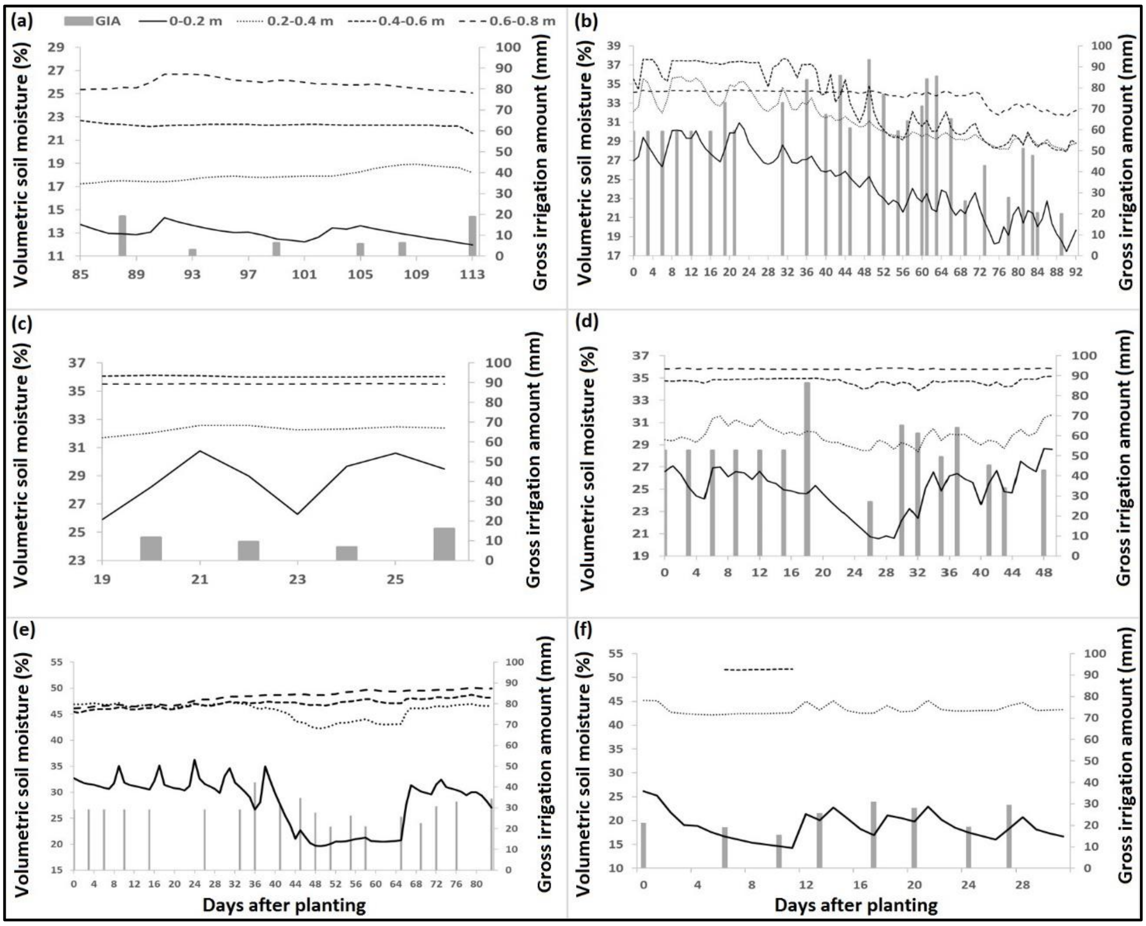

Figure 3.3 Dry-season gross irrigation amounts and soil moisture profiles in the cropping fields of (a) tomato (BF1) in 2014–2015, (b) tomato (BF1) in 2015–2016, (c) leafy vegetables (BF2) in 2014–2015, (d) leafy vegetables (BF2) in 2015–2016 in the Bongo irrigation scheme, and (e) tomato (BNF1) in 2014–2015, and (f) leafy vegetables (BNF2) in 2014–2015 in the Vea irrigation scheme.

Table 3.4 Estimation of field application efficiency in cropping systems of the Vea and the Bongo irrigation schemes in two dry seasons

Scheme/ Crop type	Field label	Net irrigation requirement (mm)	Capillary rise (mm)	Gross irrigation amount (mm)	Field application efficiency (%)
Bongo irrigation scheme		**2014–2015 dry season**			
Tomato	BF1	329	157	586	42
Tomato	BF6	431	25	1247	30
Leafy vegetable	BF2	61	130	195	52
Leafy vegetable	BF3	169	94	404	54
		2015–2016 dry season			
Tomato	BF1	362	169	1719	58
Tomato	BF6	331	27	2259	59
Leafy vegetable	BF2	186	57	792	25
Leafy vegetable	BF3	137	48	683	26
Rice	BF5	58	391	556	68
Vea irrigation scheme		**2014–2015 dry season**			
Tomato	VF1	440	18	615	58
		2015–2016 dry season			
Tomato	BNF1	220	34	1137	52
Leafy vegetable	BNF2	123	40	707	58

3.3.4 Overall system efficiency (E_s)

The E_s averaged 50% across the schemes and seasons. This was lower than the scheme management target of 65% in the VIS, which was not achieved in any of the fields due to over-irrigation (Table 3.5). The relatively high E_s in one of the two fields located along the same lateral in the VIS indicates the variable field application efficiency rather than locational differences along the canal. The community management of the small-scale

BIS did not set targets for the E_s. The system efficiency in all BIS fields showed a wide range of values between 24 and 68% across the seasons (Table 3.5).

Table 3.5 Overall system efficiency of Vea and Bongo irrigation schemes for major crops in the 2014–2015 and 2015–2016 dry seasons

Scheme/ Crop type	Field label	Length of canal section (m)	Network efficiency per canal section (%)	Overall system efficiency (%)	
Bongo irrigation scheme				**2014–2015**	**2015–2016**
Tomato	BF1	358	99.4	42	58
Tomato	BF6	378	93.5	28	55
Leafy vegetable	BF2	358	99.4	52	25
Leafy vegetable	BF3	347	94	51	24
Rice	BF5	60	99.9	n.d.	68
Vea irrigation scheme				**2014–2015**	**2015–2016**
Tomato	BN F1	30	99.7	n.d.	52
Leafy vegetable	BN F2	50	99.6	n.d.	58

n.d. = not determined

3.3.5 Delivery performance ratio

The delivery performance ratio of the Vea and the Bongo irrigation schemes was 1.8 and 0.7, respectively. In the VIS, water supply was planned to last for 4–5 continuous days owing to the poor state of canals, but was allowed to continue for 8 days because diversions from the main canal delayed water flow to the fields. In the BIS, the agreed 12-h water supply per irrigation day was interrupted by community meetings or traditional ceremonies. These interruptions occurred throughout the observation period in at least 2 days out of the 4–5 irrigation days per week. The actual duration of daily water supply averaged 8 h.

3.3.6 Relative transpiration

The reduced daily relative transpiration ($T_r < 1$) was common in crops of both schemes, reaching critical values in 2015–2016 (Figure 3.4). The T_r was most likely more reduced by over-irrigation (and resulting hypoxia) than by water stress, given that the GIA by far exceeded the NIR in most of the cropping fields and that the sub-soil moisture was often recorded above field capacity. For example, tomato field BF6 was over-irrigated at the GIA of 1,247 mm whereas the seasonal NIR was only 413mm (Table 3.4). The T_r of the BIS crops in the 2014–2015 dry season indicates that only leafy vegetables (BF2) experienced midseason water stress (average T_r = 0.76) as a result of an insufficient irrigation supply. Only the rice field in BIS exhibited optimal T_r (T_r = 1) throughout 2015–2016, which could be attributed to the aerobic irrigation practice and the groundwater contribution through capillary rise (Table 3.4). Tomato (BF1) and leafy vegetables (BF2) fields also showed T_r close to the optimum for most of the 2015–2016 season with occasional declines due to over-irrigation (Figure 3.4b, d).

3.3.7 Crop yield and water productivity

Similar ranges of tomato yields were observed across the irrigation schemes and seasons between 34.3 and 49.2 Mg ha^{-1} in the BIS, and between 35.3 and 51.3 Mg ha^{-1} in the VIS. The GIA vs. The NIR comparison indicated various degrees of over-irrigation in all fields (Table 3.4). This led to a wide range of tomato W_p values from 1.5 to 8.4 kg m^{-3} (Table 3.6).

The leafy vegetable yields were highly variable from 2.3 to 37.5 Mg ha^{-1} depending on crop type, observation season, and irrigation scheme. Overall, the BIS produced 76% higher yields of leafy vegetables than the VIS, which might be due to different types of leafy vegetable produced and, in particular, due to the legume (cowpea) intercropping by the BIS farmers in contrast to the roselle monocropping practice in the VIS. Inter-season comparisons among the BIS fields showed generally higher W_p in the 2014–2015 dry season than in the subsequent dry season.

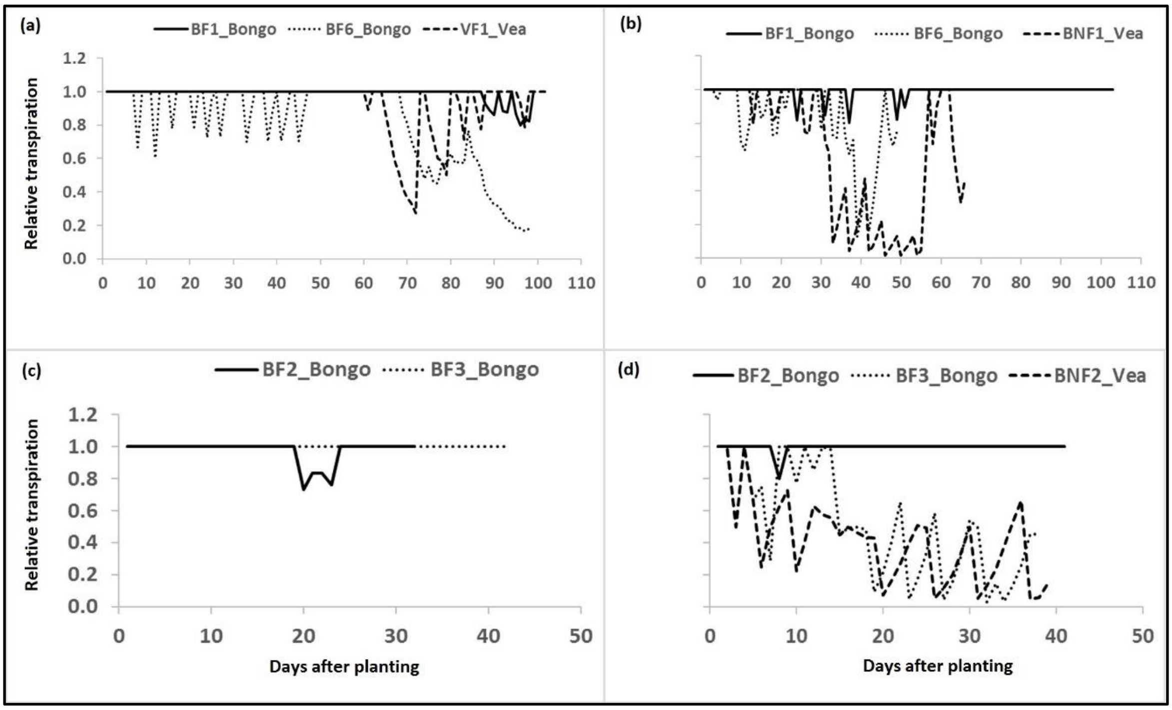

Figure 3.4 Daily relative transpiration in fields with (a) tomato in 2014–2015) and (b) in 2015–2016, (c) leafy vegetables in 2014–2015, and (d) in 2015–2016 in the Bongo and Vea irrigation schemes.

The highest crop-water productivity observed in tomato BNF1 field in 2015–2016 could be due to high yield, possibly attributable to better agronomic management considering that field application efficiency was only 52% (Table 3.4). Water stress observed in the 2014–2015 dry season in leafy vegetables (BF2) and the over-irrigation of tomato (BF6) led to lower yields than in the other fields with the same crops (BF3 and BF1, respectively).

Table 3.6 Water productivity of main irrigated crops in the Vea and the Bongo irrigation schemes

Scheme/ Crop type	Field label	Farm size (ha)	Crop yield (Mg ha^{-1})	Crop water productivity (kg m^{-3})
Bongo irrigation scheme		**2014-2015**		
Tomato	BF1	0.04	49.2	8.4
Tomato	BF6	0.10	34.3	2.7
Leafy vegetable (roselle)	BF2	0.03	17.7	8
Leafy vegetable (roselle)	BF2*	0.03	12.5	6.4
Leafy vegetable (lettuce)	BF3	0.02	37.5	9.3
		2015-2016		
Tomato	BF1	0.04	42.8	2.5
Tomato	BF6	0.09	39.6	1.5
Leafy vegetable (cowpea)	BF2	0.03	9.2	1.2
Leafy vegetable (cowpea)	BF2*	0.03	9.7	2.7
Leafy vegetable (cowpea)	BF3	0.01	10.4	2.3
Leafy vegetable (lettuce)	BF3*	0.01	8.8	1.3
Rice	BF5	0.08	5.1	0.9
Vea irrigation scheme		**2015-2016**		
Tomato	VF1	0.08	35.3	n.d.
Tomato	BNF1	0.10	51.3	4.5
Leafy vegetable (roselle)	BNF2	0.05	2.3	0.3
Leafy vegetable (roselle)	BNF2*	0.05	5	1.1

** = Second cultivation*

3.4 Discussion

3.4.1 Performance of reservoirs and water conveyance systems

High WAI observed in both dry seasons in the VIS indicates that water availability was not a constraint but rather that water resources were underutilized due to malfunctioning water delivery infrastructures. Deterioration of infrastructures in small- and medium-scale reservoir-based irrigation schemes, mostly constructed in the 1960s and 1970s, has also been alarming in several other SSA countries including but not limited to Ethiopia (Berhane et al., 2016), Benin (Djagba et al., 2014) and Burkina Faso (Poussin et al., 2015).

However, the low WAI observed in the small-scale BIS indicates insufficient water availability, exacerbating competing needs among fishery, livestock farming, and urban withdrawals. Remarkably, although the Bongo reservoir has never been desilted since its construction 55 years ago, its maximum depth only decreased from 6 m to 5.5 m (10% loss in storage capacity). Adwubi et al. (2009) reported a larger storage capacity loss (4–33%) over a period of 10 years due to siltation in the UER small-scale reservoirs. Berhane et al. (2016) observed that about 61% of the micro-dam reservoirs in Ethiopia faced siltation problems. Alemaw et al. (2013) also reported that siltation remains a big problem in reservoirs in Botswana, where the mean sediment delivery ratio was 81% and the sedimentation rate measured 1.74 Mg ha^{-1} $year^{-1}$.

3.4.2 Field application efficiency

Although the water storage of the BIS reservoir was larger at the start of the 2015–2016 season than in the previous dry season, the overall GIA used by the same irrigators also rose. Over-irrigation and double (and triple in some cases) cultivation of leafy vegetables during the same season offset the reservoir storage increment. The rise in GIA following the increase in reservoir storage agreed with the observation of Faulkner (2006) that the UER farmers tend to over-irrigate when water availability increases. Observed GIA for tomato in both seasons was about 2–5 times the values previously reported for the UER. In particular, Barry and Forkuor (2010) and Mdemu (2008) reported a GIA between 274 and 852 mm only. Considering similar methods of field-level water application across irrigation schemes in the UER, higher GIA might be related to poor irrigation scheduling, lack of measuring instruments to control water volume at field inlets, differences in water availability in the schemes as well as the shortcomings in institutional aspects of water management (Acheampong et al., 2014). Crop over-irrigation led to low field-application efficiency in most of the fields in this study. Such low values are however, not unusual for the UER and fall within the range (21–62%) reported by Yamoah-Antwi (2009) for small-scale reservoir-based irrigation schemes in the region.

Tomato yields were within the upper range or higher than those reported by Barry and Forkuor (2010) for the UER (20–36.8 Mg ha^{-1}); on the contrary, W_p values were in the lower range or smaller than those reported (2.8–9.7 kgm^{-3}). Rice yield was in the upper range of values determined by García-Bolaños et al. (2011) in Mauritania (0.6–5.7 Mg ha^{-1}) and by Poussin et al. (2015) in Burkina Faso and the UER (0.7–7.5 Mg ha^{-1}). The W_p of rice (0.9 kgm^{-3}) fell within the range (0.8–1.0 kg m^{-3}) measured by Zwart and Bastiaanssen (2004) under comparable, alternate wet-dry conditions in India. In contrast, García-Bolaños et al. (2011) reported lower rice W_p (0.3–0.6 kg m^{-3}) under a continuous flooding irrigation system in Mauritania.

3.4.3 Need for whole-system evaluation

In the medium-scale VIS, the most immediate improvement might be achieved at field level by taking into consideration that reservoir storage still appeared adequate and repair of the water delivery system would require significant investments. Both under- and over-irrigation were observed there, indicating on-farm irrigation scheduling (implicated by the field application efficiency) as the most influential factor for raising crop-water productivity as well as overall system efficiency. In the small-scale BIS, where insufficient reservoir storage and huge water losses along the conveyance network were observed, improving field-level water application alone might increase current field application efficiency from 46% to 68%. To this end, the management entity should comply with the defined irrigation schedule, which is currently compromised by frequent interruptions for community meetings.

Through the use of WAI, multiple water uses besides crop irrigation highlighted the competition that occurred in 2014–2015 in the BIS. This may explain the discrepancy with the previous conclusion that water deficit was not pronounced in the UER by Faulkner (2006) who estimated relative water supply (in the range of 2.4–5.7) by considering the water use for crop irrigation only. A similar conclusion was also made for Burkina Faso and the UER by Poussin et al. (2015), who juxtaposed gross irrigation demand only with reservoir storage capacity.

3.5 Conclusions

The whole-system evaluation of small- and medium-scale reservoir-based irrigation schemes in the UER of Ghana, taking into account their multi-purpose use, reveals that several technical factors undermined the performance of the irrigation systems. In particular, insufficient storage caused by the competing needs of a growing population compromised the performance of the small-scale scheme. In the medium-scale scheme, the deteriorated water delivery infrastructure reduced water use to less than 40% of the potential storage. Addressing these technical aspects requires significant capital investment, but even without it, the overall system efficiency might be increased from the current average of 50% to 68% through improved irrigation scheduling at field level. To this end, a rise in the field application efficiency from 58 to 68% is achievable through eliminating over-irrigation, in particular of tomato fields. This suggests the need for further research on the development of suitable irrigation scheduling tools for the prevalent cropping systems while considering the external factors that influence the field-level water applications during rainy and dry seasons. Evidently, the whole-system approach, with a consideration of all water demands, is most appropriate in the performance evaluation of reservoir-based irrigation schemes in water-scarce regions, as it makes it possible to determine which of the scheme components must be primarily improved.

4 IMPROVING DRY-SEASON CROP IRRIGATION SCHEDULES IN MEDIUM- AND SMALL-SCALE RESERVOIR-BASED IRRIGATION SCHEMES

4.1 Introduction

Prominent amongst the identified problems in the evaluated UER reservoir-based irrigation schemes (Chapter 3) was the issue of over-irrigation. This problem of over-irrigation which resulted from inappropriate irrigation schedule at field level limited the water-use potential of the irrigation schemes, as water scarcity occasionally occurred during the observation period with resultant negative impacts on other multiple users of the water reservoir. Hence, in order to utilize the potential of these schemes as far as possible, development of location-specific and context-compatible irrigation schedules for these schemes is needed.

In water-scarce environments such as the UER, sustainable soil-water management (e.g., irrigation scheduling) has been identified as the most influential among agricultural management practices, including soil fertility management, selection of crop varieties, and control of pests and diseases (Droogers and Aerts, 2005; Rockström and Barron, 2007), for enhancing food security as well as improving the smallholders' livelihoods (Molden et al., 2010; Rockström and Barron, 2007; Zwart and Bastiaanssen, 2004). Ineffective irrigation has dire consequences on crop yield, and so site-specific irrigation scheduling for crop cultivation has to be properly developed by taking into consideration the prevailing biophysical context in order that crop yield is not compromised (Ali and Talukder, 2008; Zwart and Bastiaanssen, 2004).

Consequently, crop-water-soil-atmosphere models are useful to determine the most appropriate irrigation schedules for the prevalent cropping practices and for assessing possible alternative scenarios (Greaves and Wang, 2016; Sekyi-Annan et al., 2017; Steduto et al., 2012). Among the common models capable of simulating irrigated crop growth, those requiring large inputs of primary data, for instance APSIM (Gaydon et al., 2017) and CropSyst (Sommer et al., 2008), which are not available free of charge, e.g., the irrigation scheduling model ISAREG (Fortes et al., 2005), might not be favorable for applications in SSA. The DSSAT model (Jones et al., 2003) has been commonly used to assess the impact of agronomic inputs on irrigated crop yield but at present is not suitable to evaluate the effectiveness of irrigation practices. Other models such as CROPWAT (Surendran et al., 2015) do not distinguish between evaporation (non-beneficial water consumption) and crop transpiration, and do not provide an estimation of yield or, such as EPIC (Wang and Li, 2010), apply simplified routines to evaluate the groundwater contribution to crop-water use. Modest requirement for input data, consideration of all major agro-hydrological processes, and free availability enabled many applications of the FAO AquaCrop model (Raes et al., 2012a) worldwide, including in SSA (Mabhaudhi et al., 2014; Walker et al., 2013; Wellens et al., 2013).

Current irrigation schedules in reservoir-based irrigation schemes in SSA are based on locally established rules governing access to water for irrigation, but with little consideration of crop- and site-specific water demands in terms of quantity and timing, resulting in inappropriate irrigation supply to crops (Chapter 3). For instance, in reservoir-based irrigation schemes in onion fields in the UER, the ratio of the total water supply to the gross irrigation amount (GIA) ranged between 2.4 and 5.7 during dry-season crop irrigation (Faulkner et al., 2008). The problem of over-irrigation in such schemes was further confirmed by GIAs ranging from 380 to 852 mm for dry-season tomato production in the UER (Mdemu, 2008), and between 274 and 838 mm for tomato cropping under groundwater irrigation in the same region (Barry and Forkuor, 2010). Simulations have suggested that the NIR for dry-season tomato ranges from 359 to 372 mm in the reservoir-based Koga irrigation scheme in Ethiopia (Asres, 2016), emphasizing the need and the potential to improve water management through irrigation scheduling to reduce water losses and increase productivity.

This chapter focuses on the assessment and the improvement of the efficiency and appropriateness of the traditional irrigation scheduling for the principal dry-season crops including tomato, rice and leafy vegetables, and subsequently, the development of an improved irrigation schedule for tomato cultivation using the AquaCrop model. Tomato was selected over rice and leafy vegetables for the AquaCrop modeling analysis because of the high economic value of this crop in the UER.

4.2 Materials and methods

4.2.1 Study sites

The data collection spanned two consecutive dry seasons from October 2014 to March 2015, and from November 2015 to April 2016 in the Vea and Bongo irrigation schemes. Water allocation in the VIS is supply-driven, and thus a technician implements water supply schedules for 4–5 days continuously with 3–4 days interval between schedules. In the BIS, where water allocation is demand driven, water can flow for the whole week (8 hours per day on average) except on market days, which occur twice a week. Currently, irrigators in the small-scale scheme water their crops with as much water as possible on days after the community's market days, i.e., three days in a week or any other day, resulting in waste of water (Faulkner, 2006).

Tomato (*Solanum lycopersicum*) and rice (*Oryza sativa*) monocropping and leafy vegetables intercropping including roselle (*Hibiscus sabdariffa*), lettuce (*Latuca sativa*) and cowpea (*Vigna unguiculata*) are the principal dry-season cropping systems in the UER. Local tomato varieties (namely 'buffalo') and Jasmine 85 rice were cultivated in both the BIS and the VIS. Although the crop calendar differs from one farmer to another owing to differences in planting and harvesting dates, similar farming practices exist in both schemes (see Appendices 9.9 and 9.10). Tomato was cropped once in the dry season in both the BIS and the VIS. The growing and irrigation period lasted for 113–123 days. In this period, mature tomato fruits were harvested 2–3 times. The duration of tomato seedling development was about 14 days. The growing period of rice was between 107 and 128 days including the 21 days of seedling development. In the BIS, rice is either transplanted or sown directly in the field, whereas only the transplanting was observed in the VIS. Roselle sowed by dibbling required between 30 and 49 days to mature, whereas lettuce matured in 48–52 days after planting. The seedling development of lettuce lasted for 14 days. The crop cycle of cowpea cultivated for its leaves was 34–50 days. Leafy vegetables were cropped 2–3 times in the dry season owing to the short growing cycle.

The application of NPK (0.21–0.7 Mg ha^{-1}) and ammonium sulfate fertilizer (0.1–0.34 Mg ha^{-1}) for tomato and rice, and of Karate (lambda-cyhalothrin) and DDT insecticides for tomato only was observed in both schemes. The fertilizers were applied twice in tomato and rice fields at 2–3 weeks after planting and later at 4–5 weeks after planting.

4.2.2 Model description

The AquaCrop model, developed by the Food and Agricultural Organization (FAO) of the United Nations, is a crop-water productivity model that simulates the response of crop yield to water supply. The model runs in daily time steps, which provides the basis for investigating the appropriateness of irrigation schedules to meet crop-specific demands in practical scheme operation. Consequently, the AquaCrop-based schedules have a high potential to increase crop-water productivity (Steduto et al., 2012). The model can also simulate the effect of climate variability (including variations in temperature, atmospheric carbon dioxide and available water/rainfall) on crop production (Steduto et al., 2012). Additional useful features of the model are the ability to separate soil evaporation from crop transpiration and to quantify the capillary rise from shallow groundwater.

4.2.3 Data collection and preparation

The input data required for running AquaCrop were collected from two fields under each cropping system in each irrigation scheme (Figure 3.2). The model performance, based on the simulation of aboveground dry matter (DM), was assessed with multiple inbuilt statistical indicators including the coefficient of determination (R^2), normalized root mean square error (NRMSE), Nash–Sutcliffe model efficiency coefficient (EF), and Willmott's index of agreement (*d*). The R^2 indicates the fraction of the variance in observed data explained by the model and ranges from 0 (no agreement) to 1 (perfect agreement) between simulated and observed data. Typically, $R^2 > 0.5$ is acceptable for watershed simulations (Raes et al., 2012a). The NRMSE signifies the relative difference between the simulated results and the measured data, with NRMSE < 10%, 10–20%, 20–30%, and > 30% showing excellent, good, fair, and poor model performance, respectively. The EF quantifies the relative magnitude of the residual variance in comparison to the variance of the observed data. The EF ranges between 1 and -∞, where 1 signifies a perfect match between predictions and observations, 0 indicates that predictions are as accurate as the observed means, and a negative value indicates poor predictability. The *d* quantifies the extent to which the measured data are approached by the predictions and ranges from 0 (no agreement) to 1 (perfect agreement).

Estimation of potential evapotranspiration and net irrigation requirement

Maximum and minimum air temperatures (T_{max} and T_{min}, °C), average relative humidity (RH, %), wind speed (U, m s^{-1}) and solar radiation (R_s, W m^{-2}) were measured by weather stations installed near the study schemes, at 10° 54’ 54.1” N and 0° 49’ 35.3” W in the BIS, and 10° 50’ 44.6” N and 0° 54’ 43.9” W in the VIS. The solar radiation data in 2014–2015 and wind speed data in 2015–2016 measured in the BIS were used for the analysis in the VIS owing to unavailable local data. Potential ET was calculated based on the Penman-Monteith equation using the FAO ET_0 calculator as follows (Allen et al., 1998):

$$ET_o = \frac{1}{\lambda_w} \frac{\Delta(R_n - G) + \rho_a C_p (e_s - e_a)}{\Delta + \gamma_a \left(1 + \frac{r_c}{r_a}\right)} \tag{4.1}$$

where, ET_0 is potential evapotranspiration (mm day^{-1}), R_n is net radiation (W m^{-2}), G is soil heat flux (W m^{-2}), (e_s–e_a) is vapour pressure deficit of the air (kPa), ρ_a is mean air density at constant pressure (kg m^{-3}) C_p is specific heat of the air (MJ kg^{-1} $°C^{-1}$), Δ is slope of the saturation vapour pressure-temperature relationship (kPa $°C^{-1}$), λ_w is latent heat of vaporization (MJ kg^{-1}), γ_a is psychrometric constant (kPa $°C^{-1}$), r_c is crop resistance (s m^{-1}), and r_a is aerodynamic resistance (s m^{-1}).

Next, the NIR was calculated based on the actual ET computed in the AquaCrop as follows (Doorenbos, 1997; Steduto et al., 2012):

$$NIR = \sum_{i=1}^{n}[(K_{cb}+K_e)ET_{o_i} - P_{e_i} - CR_i - W_{b_i}] \quad (4.2)$$

where n is the number of days in the crop cycle, K_{cb} is the basal crop coefficient, K_e is evaporation coefficient, P_e is effective rainfall (mm), CR is capillary rise (mm), and W_b is stored soil water (mm).

Crop growth and yield parameters

Sampling areas were demarcated within all selected fields for the collection of total above-ground biomass (AGB) (Bell and Fischer, 1994). For row-cropped fields (tomato and leafy vegetables), three rows were defined for biomass sampling. For broadcast fields (rice), a 1.5-m wide area which extended to the end of the field was demarcated. The AGB was collected bi-weekly, i.e., four times during the vegetative and reproduction stages, and once at harvest. Sampling usually started when the crops were well established about 21 days after planting. On each sampling day, three samples were collected per field. In particular, in the row-cropped fields, one sample was taken from each defined row by cutting all plants along a 1-m rod. For rice, the 1-m² quadrat (or a 0.25-m² quadrat depending on the size of the field) was randomly thrown three times in the demarcated area and the plants in the quadrat were cut. At harvest, two 8-m row sections in each of the selected row-cropped fields, and an 8-m² section in rice fields were demarcated for AGB measurement. AGB was sampled and weighed as the yield components, i.e., tomato fruits, rice grains and leaves of the leafy vegetables. The samples were weighed, oven-dried at 70–90°C until constant weight for at least 72 hours and subsequently the AGB and the yield components were weighed (Bell and Fischer, 1994). The planting dates differed from one farmer to another, hence the growth stages of the crops at the time of sampling were not the same. Harvest index (HI) was estimated as the ratio of the dry yield component to total AGB. Because of the short crop cycle of leafy vegetables, only two AGB samplings before the final harvest were possible. The tomato yields in BF1, VF1 and BNF1 could not be assessed during the 2015–2016 season owing to the early onset of the rainy season in 2016, leading to waterlogging and failed tomato yields. Tomato yield measurements were therefore conducted in the neighboring fields characterized by similar soil conditions and farming practices. The HI of leafy vegetables could not be computed because their AGB was harvested by farmers for consumption or sale. Owing to failed rice crops in the BIS and technical challenges in the VIS, rice yield could not be assessed in the 2014–2015 dry season.

Plant density (PD) was determined in all sampling fields. Row spacing was measured as the average distance between two adjacent rows at five random locations in the field (Bell and Fischer, 1994).

The leaf area index (LAI) was measured bi-weekly with the SunScan probe (SS1-UM-2.0) at five random locations at each field. It was converted into canopy cover (CC) using Eq. 4.3 developed for maize and soybean but applicable to other crops with similar leaf shapes (Steduto et al., 2012). The LAI measurements were interrupted in the 2015–2016 dry season due to technical challenges.

$$CC = 1.005[1 - \exp(-0.6LAI)]^{1.2} \tag{4.3}$$

Maximum rooting depth (RD) was measured by manual excavations of at least three plants per crop at harvest time. A summary of all crop growth and yield parameters measured and details of their measurements each season are provided in Appendices 14–16.

The GIAs at the farm inlets were determined as described in section 3.2.5.

Groundwater monitoring

Groundwater was monitored from October 1, 2014 to May 11, 2016 to analyze the impact of the groundwater table on water fluxes. Seven georeferenced wells were installed in the irrigable area of the VIS and five in the BIS (Figure 3.2) at characteristic locations, such as valley bottoms, lateral sites, sites near the dam, and in the middle of the schemes. PVC pipes perforated up to 1 m from the base were used. The depths of the wells ranged from 2.7 to 5.5 m in the VIS and from 2 to 4.9 m in the BIS. An electric contact meter (Seba KLL 077) was used to measure the depth to groundwater table weekly throughout the 2014–2016 observation period.

Capillary rise was estimated in AquaCrop based on soil type and hydraulic characteristics (Raes et al., 2012b) as follows:

$$CR = \exp\left(\frac{\ln(z) - b}{a}\right) \quad (4.4)$$

where CR is the expected capillary rise in mm day^{-1}, z is the depth to groundwater table in m, and a and b are coefficients specific to the soil type and the hydraulic characteristics.

4.2.4 Model parameterization and validation for tomato

The 2014–2015 dry-season dataset from BF1 was used to parameterize the AquaCrop model, and the inter-farm model validation was done using the 2014–2015 dataset from the BF6 field. For the inter-seasonal validation, the dataset from the BF1 field collected in 2015–2016 was used. Data from the other tomato fields (VF1 and BNF1) were either unavailable or incomplete owing to technical and agronomic (crop disease attack) challenges in 2014–2015, and the early onset of rainfall destroying the crops in 2016.

The parameters modified in the model were in relation to the weather, soil, and agronomic practices (Table 4.1). All the default crop-specific parameters for tomato were used in the simulation. The climate file in daily time steps for the period May 21, 2014 (beginning of the rainfed farming season in 2014) to May 24, 2016 (end of the 2015–2016 dry-season farming) was created using the AquaCrop ET_o file, maximum and minimum temperature file, and a rainfall file.

Table 4.1 Modified parameters and field data for parameterizing and validating AquaCrop for tomato.

Data required	Model parameterization	Inter-farm model validation	Inter-seasonal validation
Site conditions			
Cropping field	BF1 (2014–2015)	BF6 (2014–2015)	BF1 (2015–2016)
Crop variety	'Buffalo'	'Buffalo'	'Buffalo'
Growing cycle	October 22, 2014 – February 11, 2015	November 11, 2014 – March 6, 2015	November 23, 2015 – March 18, 2016
Planting method	Transplanting	Transplanting	Transplanting
Soil fertility in relation to biomass	Moderate	Moderate	Moderate
Initial canopy cover	Very low cover	Very low cover	Very low cover
Maximum canopy cover	Fairly covered	Fairly covered	Fairly covered
Maximum rooting depth	0.35 m	0.37 m	0.28 m
Harvest index	0.29	0.29	0.21
Crop development	In growing degree days	In growing degree days	In growing degree days
Field management			
Soil surface cover	No mulch	No mulch	No mulch
Irrigation practice	Irrigation amount per event in mm from BF1	Irrigation amount per event in mm from BF6	Irrigation amount per event in mm from BF6
Soil physical characteristics	Field capacity, wilting point, soil moisture, texture, and thickness of soil layer from soil pit 1 in BF1	Field capacity, wilting point, soil moisture, texture, and thickness of soil layer field from soil pit 2 near BF6	Field capacity, wilting point, soil moisture, texture, and thickness of soil layer from soil pit 1 in BF1

Groundwater level	Weekly depth to groundwater table from BR well	Weekly depth to groundwater table from BD well	Weekly depth to groundwater table from BR well
Simulation period	Calendar of growing cycle	Calendar of growing cycle	Calendar of growing cycle
Field data file	Aboveground dry matter from BF1	Aboveground dry matter from BF6	Aboveground dry matter from BF1

Note: BD= Bongo downslope well, BR=Bongo right well, BF = Bongo field

4.2.5 Improved irrigation scheduling for tomato cultivation

Datasets from tomato fields (BF1 and BF6) in 2014–2015 were used to optimize the irrigation schedule. Irrigation files for each field were created for the furrow irrigation method. The time criterion selected was 'Allowable depletion of 80% of readily available water' and the irrigation depth criterion used was 'Back to field capacity'. The irrigation water quality was specified as 'excellent' assuming a negligible salinity of irrigation water.

Next, GIA was estimated from the NIR assuming a mean E_a of 55% (Table 3.4). In order to translate the observations into useful information for irrigators in the UER, Eqs. 4.5 and 4.6 were generated from a graph of GIA against irrigation duration observed under the traditional irrigation practice for determining the depth of water in the canal (gauge reading (GR), mm) and the duration of irrigation (DI, s) required to achieve the estimated GIA, respectively.

$$GR = -0.03GIA^3 + 3.4GIA^2 - 133.44GIA + 1769.48 \tag{4.5}$$

$$DI = 1.11GIA^3 - 132.01GIA^2 + 5165.04GIA - 64897.57 \tag{4.6}$$

4.3 Results

4.3.1 Reference evapotranspiration in the dry season

Maximum ET_0 values (8.5–9.2 mm day^{-1} in the BIS; 7.9–8.6 mm day^{-1} in the VIS) were recorded in February-March, while the minimum values (3–4.5 mm day^{-1} in the BIS; 2.7–4.4 mm day^{-1} in the VIS) were observed in late October-November in both study schemes (Figure 4.1), which can be explained by the temperature, radiation and humidity levels in those periods. The relatively low ET_0 values observed in the VIS during the 2014–2015 season could be attributed to the lower wind speed observed in the area as well as a relatively humid micro-climate created by the presence of the bigger Vea reservoir. Similar observations were made by Mdemu (2008) in the Tono irrigation scheme located in the same region. The similar ET_0 values computed for the 2015–2016 dry season in the BIS and the VIS (Figure 4.1b) most probably resulted from using the same data on wind speed and solar radiation for both schemes in that period as local data were not available.

4.3.2 Crop growth parameters

The PD of tomato was slightly higher in the BIS (3.3–3.5 plants m^{-2} in 2014–2015, and 3.6–4.2 plants m^{-2} in 2015–2016) than in the VIS (2.6 plants m^{-2} in 2014–2015, and 3.3–3.5 plants m^{-2} in 2015–2016) (Table 4.1). The difference was partly due to the narrower interrow spacing observed in the BIS (0.28–0.35 m) compared to that in the VIS (0.25–0.54 m). The remarkably low tomato DM in the Vea BNF1 field in 2014–2015 was due to the impact of plant root disease (Figure 4.2). The PD of leafy vegetables ranged between 51 and 200 plants m^{-2} in the BIS, and between 91 and 118 plants m^{-2} in the VIS.

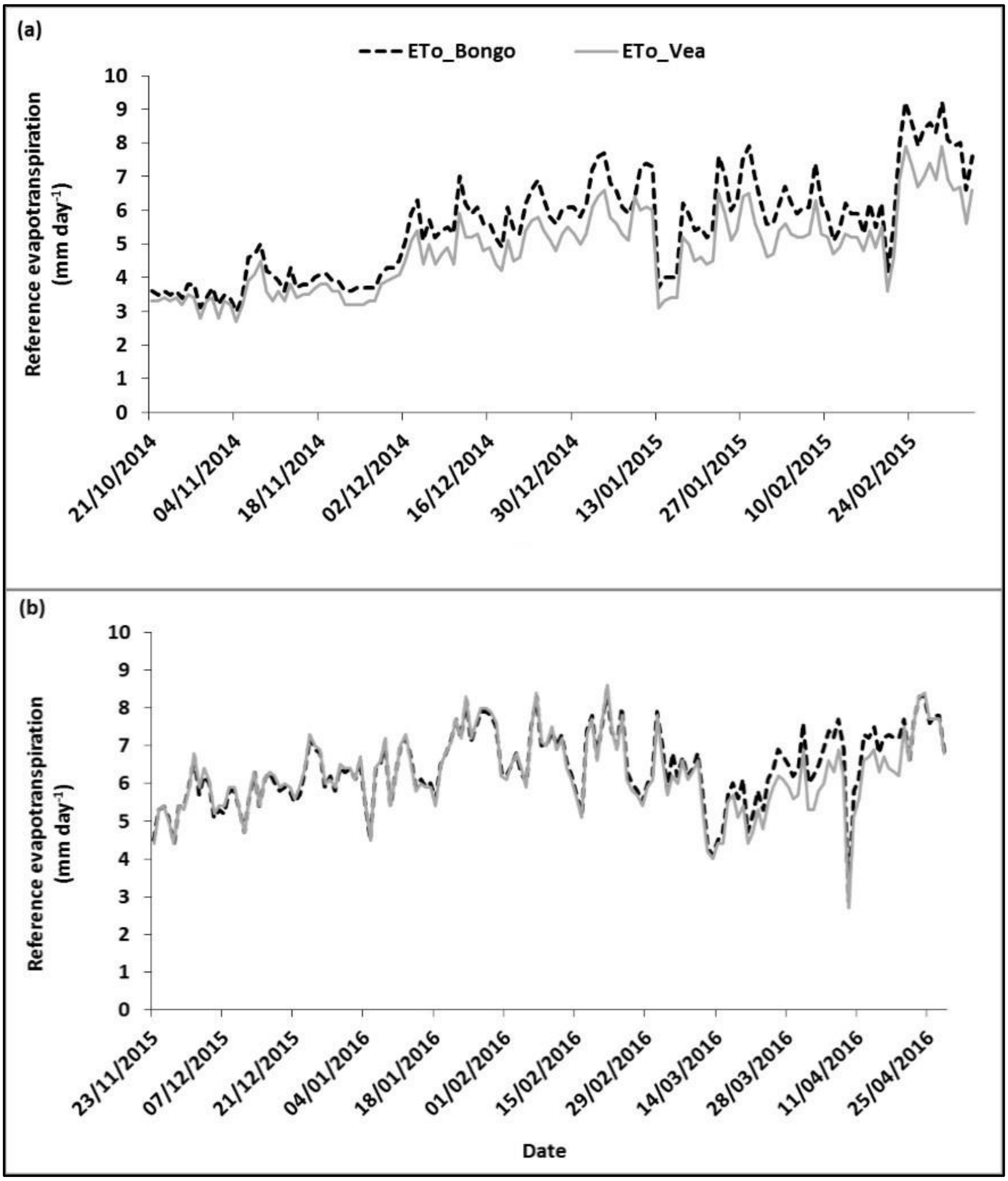

Figure 4.1 Daily reference evapotranspiration (ET_0) in the Bongo and Vea irrigation schemes observed in (a) 2014–2015 and in (b) 2015–2016 dry seasons.

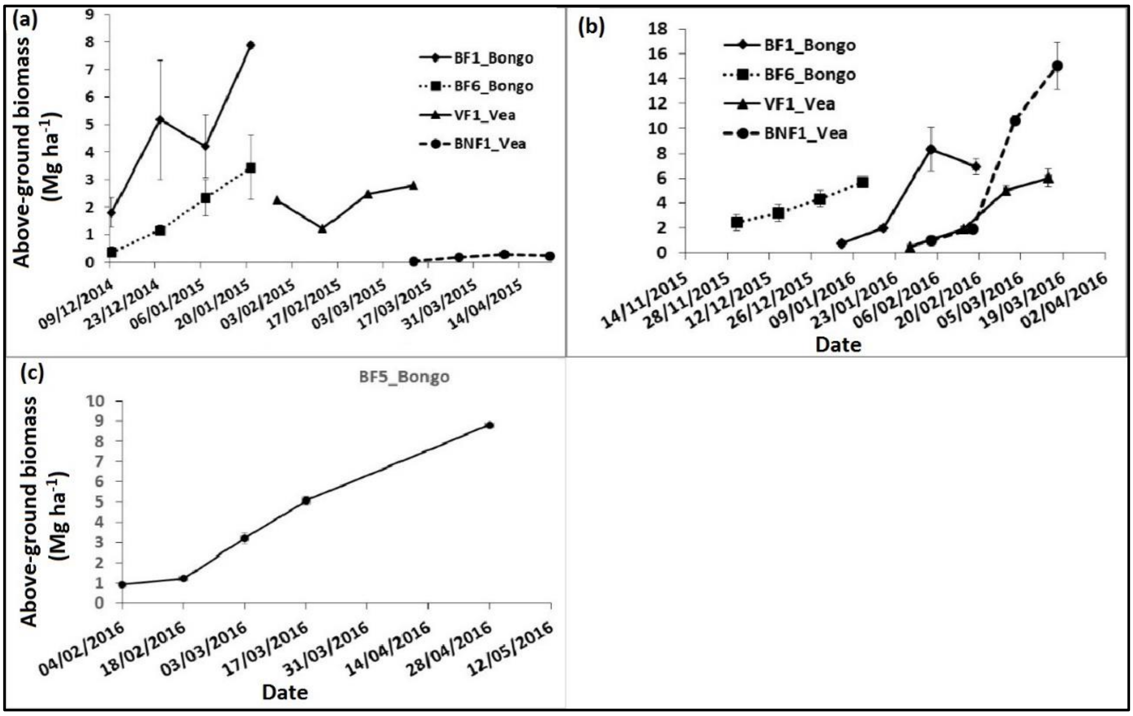

Figure 4.2 Above-ground biomass of (a) tomato in 2014–2015, (b) tomato in 2015–2016, and (c) rice in 2015–2016 during the irrigated dry season in the Bongo and Vea irrigation schemes.

The downward trend of the LAI of tomato observed in the BIS in 2014–2015 might be due to an insufficient water supply in the later part of the dry season. In contrast, the upward trend of the LAI in the VIS reflects an adequate water supply (Figure 4.3). The maximum RD of tomato, leafy vegetables and rice ranged between 0.14 and 0.37 m (Table 4.1), a result of the shallow soil depth, which does not exceed 0.4 m in the UER.

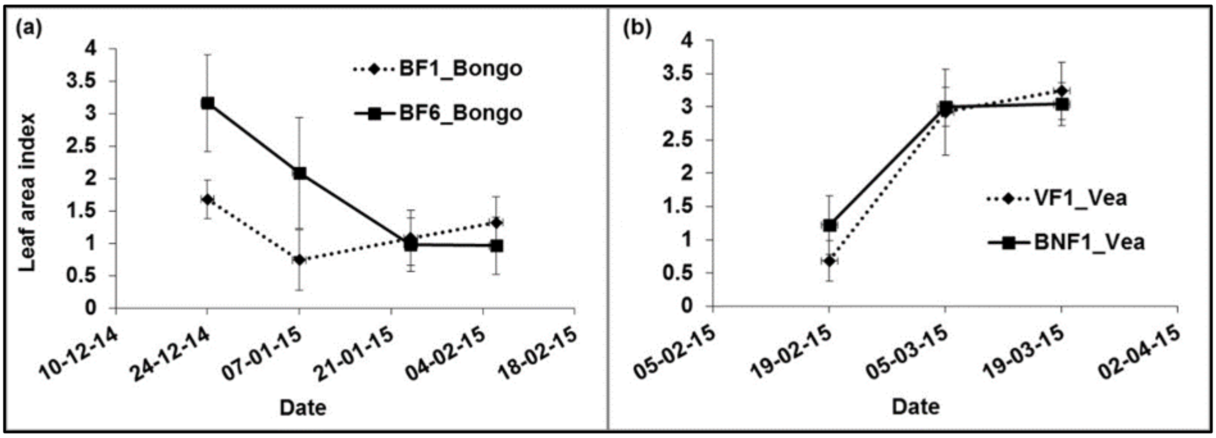

Figure 4.3 Leaf area index of irrigated tomato during the 2014–2015 dry season in the (a) Bongo and (b) Vea irrigation schemes

4.3.3 Crop yield components

Similar crop yields were observed across the irrigation schemes with remarkable differences between fields (section 3.3.7; Table 4.1). Low HI values of tomato in the range of 0.21–0.3 were determined across irrigation schemes and seasons. In contrast, the HI of rice in the BIS was high (0.58). The yield of rough rice was 5.09 Mg ha^{-1}, whereas that of white milled rice amounted to 2.4 Mg ha^{-1}.

4.3.4 Groundwater level and capillary rise

The average depth to the groundwater table varied between 0.7 and 2.8 m in the VIS, and between 0.6 and 1.3 m in the BIS during 2014–2016 (Figure 4.4). In the BIS, the soil waterlogging detected in the BM well occurred in August, and the deepest level (3 m measured in the BD well) was observed in May. The BNF2 well in the VIS recorded the shallowest groundwater level (0.1 m) in August, while the VF1 well measured the deepest groundwater level (3.4 m) in May. The rise in the groundwater table in August most probably resulted from the rainfall recharge.

Table 4.1 Irrigated crop growth and yield components in the Bongo and Vea irrigation schemes during the 2014–2015 and 2015–2016 dry seasons

Crop type	Field label	Plant density (plants m^{-2})	Maximum rooting depth (m)	Fresh yield (Mg ha^{-1})	Dry yield (Mg ha^{-1})	Harvest index
Bongo irrigation scheme			**2014–2015**			
Tomato	BF1	3.5	0.35	49.24	2.26	0.29
Tomato	BF6	3.3	0.37	34.28	2.49	n.d.
Roselle	BF2	161	0.20	17.65	n.d.	n.d.
Roselle	BF2*	55.7	0.20	12.5	n.d.	n.d.
Cowpea	BF2*	31.1	0.20	22.79	n.d.	n.d.
Lettuce	BF3	6.3	0.24	37.49	n.d.	n.d.
			2015–2016			
Tomato	BF1	3.6	0.28	42.83	1.42	0.22
Tomato	BF6	4.2	n.d.	39.55	1.57	0.21
Cowpea	BF2	25.7	0.14	9.19	n.d.	n.d.
Cowpea	BF2*	84	0.14	9.67	n.d.	n.d.
Cowpea	BF3	49.3	n.d.	10.42	n.d.	n.d.
Roselle	BF2**	104.5	0.27	9.74	n.d.	n.d.
Lettuce	BF3*	5.5	n.d.	8.83	n.d.	n.d.
Rice	BF5	117.8	0.27	n.d.	5.09	0.58
Vea irrigation scheme			**2015–2016**			
Tomato	VF1	3.3	0.24	35.34	1.56	0.29
Tomato	BNF1	3.5	0.29	51.25	2.20	0.30
Roselle	BNF2	38.8	0.22	2.33	n.d.	n.d.
Roselle	BNF2*	116.3	0.22	5	n.d.	n.d.

** = Second cultivation in the season, ** = Third cultivation in the season, n.d. = not determined/applicable*

Furthermore, the groundwater level was influenced by nearby streams, reservoirs, and fish ponds. For example, the BU well in the BIS and the VU, BNM and BoN wells in the VIS exhibited stable and relatively shallow groundwater levels due to their proximity to the Bongo reservoir, Vea fish ponds, and streams, even when deep groundwater levels were recorded at other wells (Figure 4.4). Irrigation events also impacted on the water table. For instance, the groundwater level in the BF1 well in the tomato field increased steadily from the beginning of the dry season and declined from March 4, 2015, when 2014–2015 dry-season irrigation was discontinued. However, the VF1 and BNF2 wells in the VIS in the tomato and leafy vegetable fields, respectively, exhibited rather variable groundwater levels even during the irrigation period and a downward trend after the end of the irrigation period.

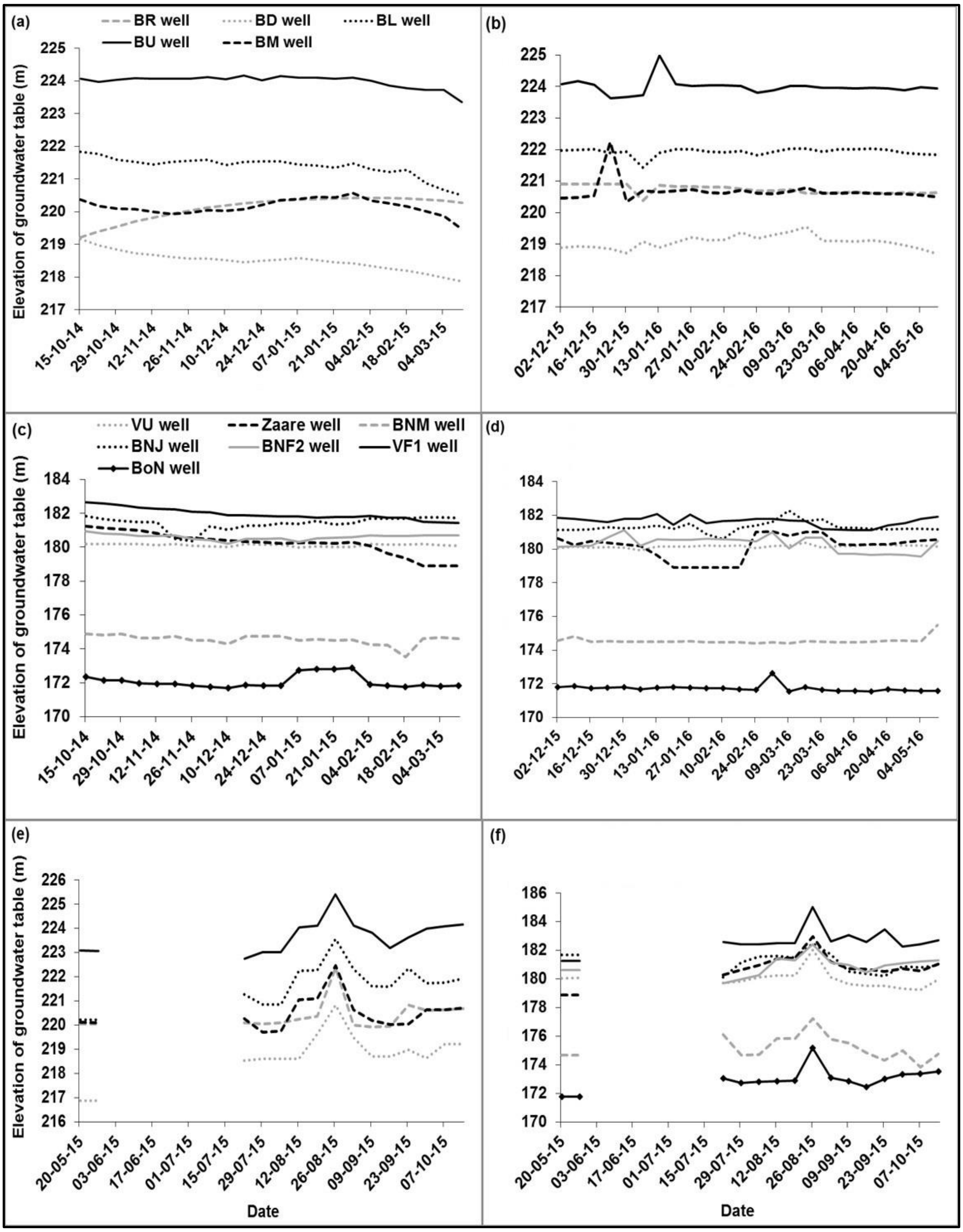

Figure 4.4 Elevation of the groundwater table during (a) 2014–2015 dry season in Bongo (b) 2015–2016 dry season in Bongo (c) 2014–2015 dry season in Vea (d) 2015–2016 dry season in Vea (e) 2015 rainy season in Bongo and (f) 2015 rainy season in Vea.

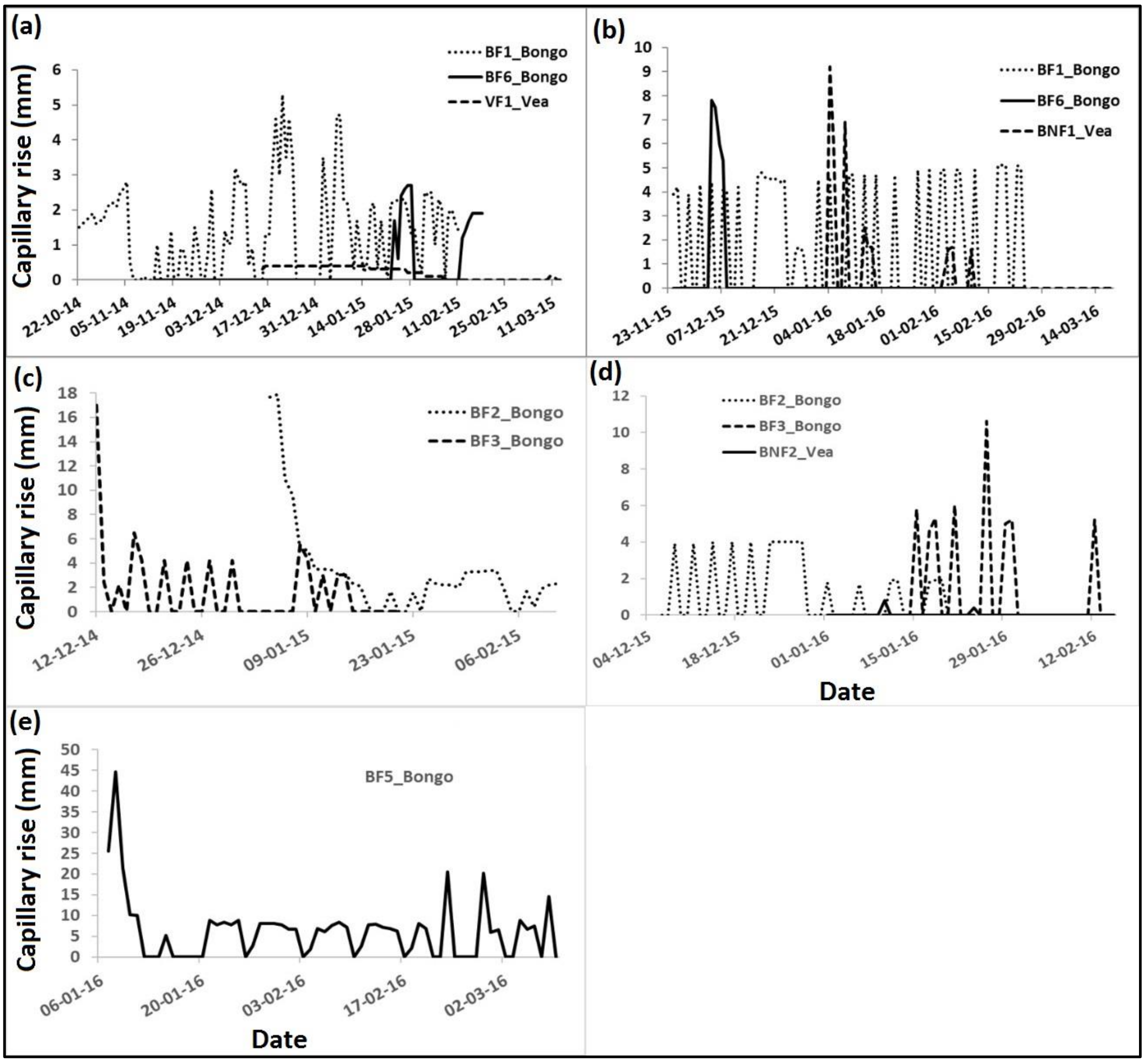

Figure 4.5 Daily capillary rise into the root zone of dry-season irrigated (a) tomato in 2014–2015, (b) tomato in 2015–2016, (c) leafy vegetables in 2014–2015, (d) leafy vegetables in 2015–2016, and (e) rice in 2015–2016 simulated in AquaCrop.

The simulated capillary rise (CR) into the root-zone of tomato was 18–157 mm, while in leafy vegetable fields it was 40–130 mm across irrigation schemes and cropping seasons. The CR into the rice field in the BIS was as high as 391 mm in 2015–2016, which could be due to its closeness to the Bongo reservoir, and it thus benefited from seepage losses from the reservoir during the dry periods of the crop cycle (Figure 4.5).

4.3.5 Traditional irrigation scheduling

The observed GIA for all the irrigated crops was lower in 2014–2015 than in 2015–2016 in both schemes (Tables 4.2 and 4.3). Particularly in the BIS, the irrigation interval in all the cropping fields was generally shorter in 2015–2016 than in the previous dry season owing to the increased availability of water in the Bongo reservoir. Across both irrigation schemes and both dry seasons, the overall range of GIA in tomato fields was 21–67 mm per irrigation event and 584–2,559 mm per season. These values for leafy vegetables were 17–62 mm and 195–707 mm, respectively, whereas those for rice were 10–16 mm and approximately 556 mm, respectively. The number of irrigation events for tomato ranged between 20 and 29 in both dry seasons. These values for leafy vegetables and rice were 9–23 and 10–16, respectively. The relatively low GIA for leafy vegetables was due to the short crop cycle.

Table 4.2 Observed field-level irrigation practices for cropping systems in the Bongo and Vea irrigation schemes during the 2014–2015 dry season

Crop type	Field label	Gross irrigation amount per crop cycle (mm)	Gross irrigation amount per event (mm)	Irrigation interval (day)	Water productivity (kg m^{-3})
Bongo irrigation scheme					
Tomato	BF1	586	19–50	4	8.4
Tomato	BF6	1247	17–137	5	2.7
Roselle	BF2	221	17–19	3	8
Roselle	BF2*	195	7–40	3	6.4
Lettuce	BF3	404	8–38	4	9.3
Rice	BF5	n.d.	13–34	8	n.d.
Vea irrigation scheme					
Tomato	VF1	615	13–35	5	n.d.
Tomato	BNF1	584	21–42	5	n.d.
Roselle	BNF2	287	16–40	4	n.d.
Rice	VF2	n.d.	29–48	7	n.d.
Rice	BoNF2	n.d.	15–27	7	n.d.

n.d. = not determined

4.3.6 Model performance

The results of model evaluation for tomato DM indicated a good agreement (EF=0.65–0.83, and d=0.87–0.96) and acceptable error margins (NRMSE=17.7–42%) (Figure 4.6).

Table 4.3 Observed field-level irrigation practices for cropping systems in the Bongo and Vea irrigation schemes during the 2015–2016 dry season

Crop type	Field label	Gross irrigation amount per crop cycle (mm)	Gross irrigation amount per event (mm)	Irrigation interval (day)	Water productivity (kg m^{-3})
Bongo irrigation scheme					
Tomato	BF1	1719	20–93	3	2.5
Tomato	BF6	2559	14–133	2	1.5
Cowpea	BF2	359	29–58	4	1.2
Cowpea	BF3	454	12–99	4	2.3
Lettuce	BF3*	683	22–83	3	1.3
Rice	BF5	556	25–113	7	0.9
Vea irrigation scheme					
Tomato	BNF1	1137	33–79	4	4.5
Roselle	BNF2	707	43–99	4	0.3
Roselle	BNF2*	435	43–93	4	1.1

** = Second cultivation*

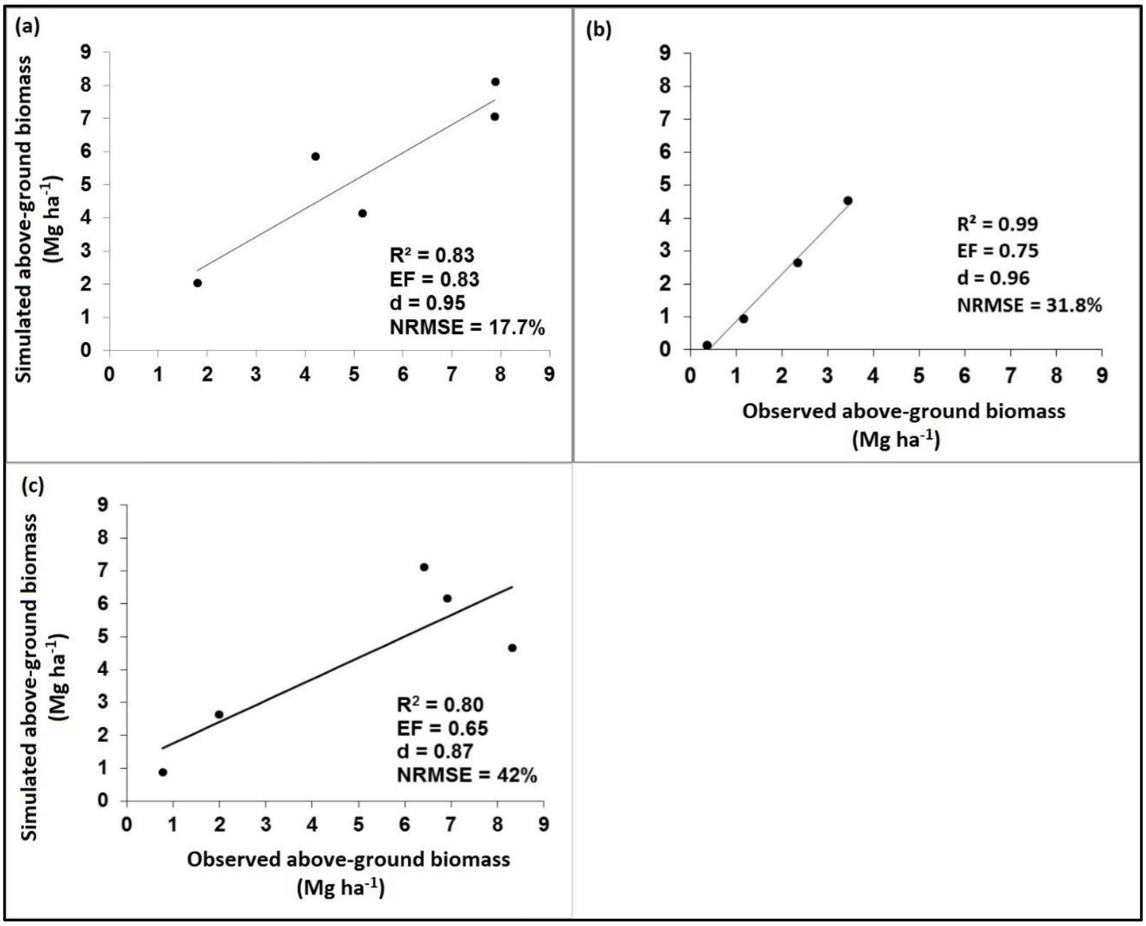

Figure 4.6 Evaluation of Aquacrop-simulated and observed aboveground biomass of dry-season irrigated tomato in (a) BF1 in 2014–2015, (b) BF6 in 2014–2015, and (c) in BF1 in 2015–2016, in the Bongo irrigation scheme.

4.3.7 Improved irrigation schedule for tomato

The optimized irrigation schedule for the dry-season tomato cropping indicated the need for longer irrigation intervals (6–13 days) in the early crop growth stage and during ripening. In contrast, in the flowering and yield formation stages, irrigation intervals should be shorter (2–8 days) (Figure 4.7). The simulated NIR for tomato ranged from 21 to 29 mm per irrigation event and from 311 to 495 mm per season. The GIA for tomato was estimated as 38–52 mm per irrigation event and 566–900 mm per season, assuming a 55% application efficiency.

The improved irrigation schedule would result in a 4–14% yield increment while saving 130–1,325 mm (22–52% of GIA) of water, which is otherwise lost through percolation beyond the root zone under the traditional irrigation practice in either scheme (Table 4.4).

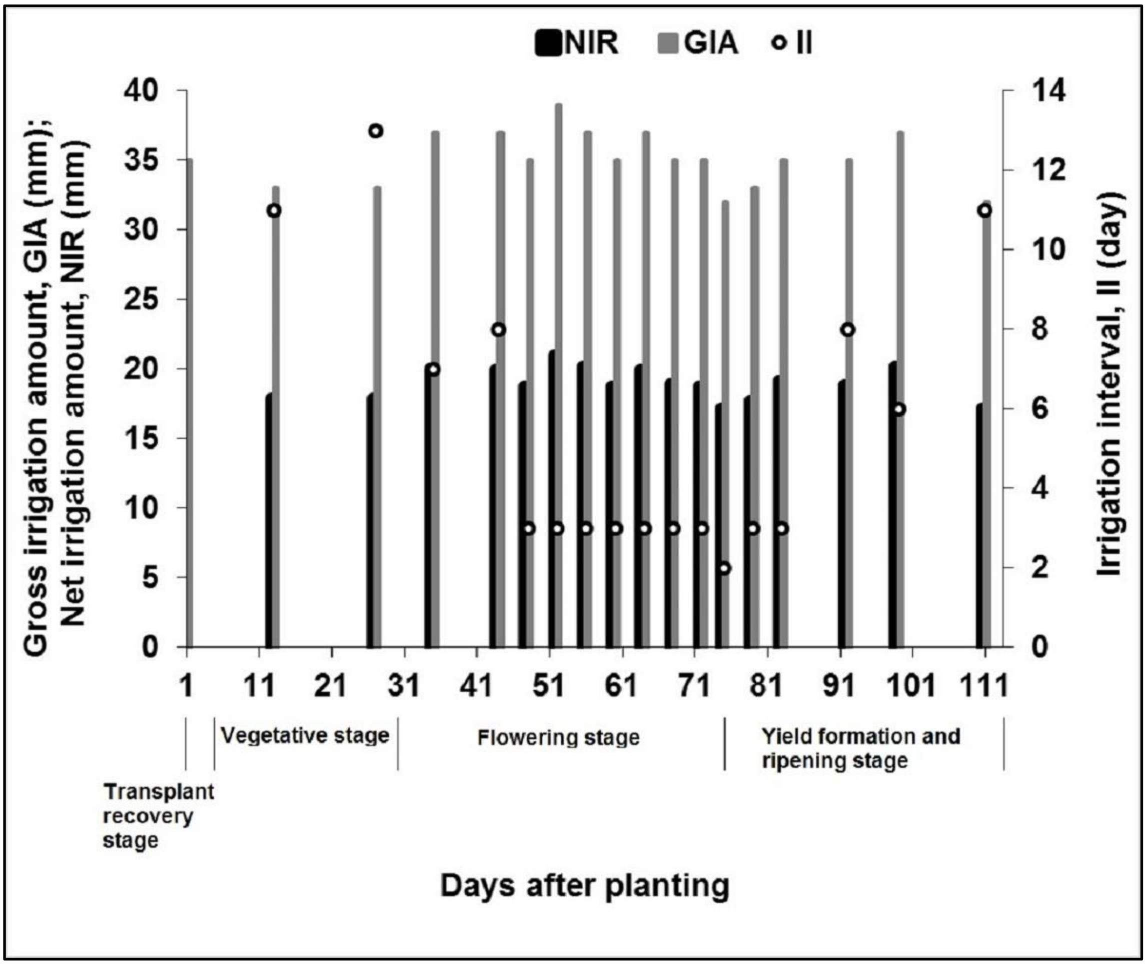

Figure 4.7 Improved irrigation schedule for tomato cultivation during the dry season based on the example of BF1 field in the Bongo irrigation scheme. Gross irrigation amount was estimated using a field application efficiency of 55% (Table 3.4).

Table 4.4 Potential water saving and yield increase under the improved irrigation schedule during the dry seasons of 2014–2016 as simulated in AquaCrop.

Field label	Potential water saving (mm)	Tomato yield under traditional irrigation (Mg ha^{-1})	Tomato yield under improved irrigation (Mg ha^{-1})	Potential yield increase (%)
BF1 (2014–2015)	130	2.30	2.40	4
BF6 (2014–2015)	775	2.01	2.30	14
BF1 (2015–2016)	1,325	1.58	1.79	14

4.4 Discussion

4.4.1 Crop yield

The yields of fresh tomato fruits were similar across schemes but varied remarkably between fields owing to differences in field-level agronomic and irrigation practices and constraints. For instance, the tomato root disease in the VIS field impacted negatively on the yield, as the application of insecticides protected only the aboveground biomass. Over-irrigated tomato in 2015–2016 showed high fresh yields and a higher water content of these fruits, i.e., 95% vs 93% in water-scarce 2014–2015. The values of tomato fresh yield corresponded to the upper ranges measured by Barry and Forkuor (2010) who reported 20–36.8 Mg ha^{-1} of fresh tomato yields in the UER, but were higher than the 18 Mg ha^{-1} reported by Adu-Dapaah and Oppong-Konadu (2002) for rainfed tomato production in the Ashanti and Brong Ahafo regions of Ghana. These findings reflect the positive impact of irrigation. However, the lower HI of tomato observed in our study (0.21–0.3), compared to values (0.5–0.65) reported by Steduto et al. (2012) for rainfed tomato in drylands, could be partly due to over-irrigation. The excessive water use was reflected in the low field application efficiencies (30–59%) characteristic of almost all the examined fields (Table 3.4).

The high yields of roselle in the fields in BIS could be due to the influence of mixed cropping with cowpea (a leguminous crop) practiced by the farmers (section

3.3.7). The observed yield of leafy vegetables was consistent with the values (1.3–7.5 Mg ha^{-1}) previously reported by Poussin et al. (2015) for the UER.

The rice yield was consistent with those of Steduto et al. (2012), who reported yield of rough rice under aerobic conditions in the range of 4–6 Mg ha^{-1}. Poussin et al. (2015) and García-Bolaños et al. (2011) measured average yields of rough rice of about 4.1 Mg ha^{-1} and 3.4 Mg ha^{-1} in Burkina Faso and Mauritania, respectively (section 3.3.7). The HI of rice derived in this study, however, was higher than the 0.45–0.5 reported by Steduto et al. (2012). This high rice yield could be due to an improved soil aeration resulting from the alternate wet-dry method of irrigation practiced in the rice fields.

4.4.2 Irrigation practice

The examination of field-level irrigation practices during the dry season revealed ineffective water application for crop production resulting in over-irrigation in both schemes, mainly due to lack of consideration of the crop growth stages and water storage characteristics of the soil. Over-irrigation was signified by the high GIA in the water-abundant 2015–2016 season, when farmers in both schemes used more water by shortening irrigation intervals (Table 4.3), leading to lower water productivity than in the previous, water-scarce season. Because of the lack of appropriate irrigation scheduling and the absence of flow measuring devices in the canals, farmers applied as much water as possible especially to the tomato crop, and further increased the water application rate with increasing water availability in the reservoir. Faulkner et al. (2008) also observed the tendency for excessive water use in response to increasing water availability and attributed this phenomenon to the lack of knowledge of efficient and effective water application at field level. Moreover, the GIAs of tomato in our study were 100–400% higher than the range of values (274 and 852 mm) previously reported for the UER (Barry and Forkuor, 2010; Mdemu, 2008), thus confirming the need for water saving.

4.4.3 Improved irrigation scheduling

The need to adjust irrigation schedules to the local hydro-geological conditions is suggested by the modelling analysis. For example, a significant contribution of capillary rise from the groundwater was shown to satisfy the NIR of crops. However, the groundwater contribution was highly variable, reflecting the spatial variability in hydro-geological characteristics of the cropping fields. According to Bos et al. (2009), there could be varying contributions of shallow groundwater (≤ 3 m) to the root-zone soil moisture in fine-textured soils such as those mostly found in the Bongo and Vea irrigation schemes. The need to account for this variability complicates the development and application of improved farmer irrigation scheduling in the UER.

The observed increases in tomato yield (4–14%) under the improved irrigation schedule most likely resulted from the reduction of the negative effect of over-irrigation on crop yield, as the over-irrigated cropping fields showed the highest potential (14%) to increase yields under the improved irrigation schedule. The simulated magnitude of water saving in the reservoir-based irrigation schemes, which was 22–52% of the GIA under the current irrigation practices, indicates that improving irrigation schedules offers considerable potential for water saving in the dry season in the UER irrigation systems. Overall, however, the improvement of field-level irrigation scheduling alone might not be sufficient for optimizing water productivity and availability in the schemes (section 3.4.3). To achieve full benefits, equipping irrigation infrastructure with discharge-measuring and dosage structures, and repair of the deteriorating water conveyance and distribution sub-systems in the UER would be necessary (Ali and Talukder, 2008; Pereira, 2007). These interventions to upgrade infrastructure would need to be accompanied by training of irrigators in handling these facilities, and by further development of water management institutions towards reliable implementation of the recommended irrigation schedules. Furthermore, the improved irrigation schedule developed for tomato cultivation should undergo on-farm testing with farmers' participation to facilitate its out-scaling.

4.5 Conclusions

The potential increment of tomato yield under the improved irrigation schedule ranged between 4 and 14% while saving 130–1,325 mm of irrigation water. These results show that improving traditional irrigation scheduling under the current performance of the schemes would not only enhance water saving during the dry season for the competing water demands but also increase the yield of irrigated crops. Therefore, irrigation scheduling considering site and crop specificity is an appropriate tool for raising irrigation efficiency and water productivity, and subsequently for addressing water scarcity in multi-purpose irrigation schemes in semi-arid environments of Sub-Saharan Africa. The AquaCrop model has proven to be a reliable tool for developing improved irrigation schedules for tomato cultivation in the UER, as it aided in the assessment of the efficiency of the traditional irrigation practices and in development of site-specific irrigation schedules for this commercially important crop. Parameterized using field data collected in reservoir-based irrigation schemes, the AquaCrop model can be further used for improving the irrigation schedule for other cropping systems.

5 POTENTIAL OF SMALL- AND MEDIUM-SCALE RESERVOIR-BASED IRRIGATION SCHEMES FOR SUPPLEMENTAL IRRIGATION IN THE RAINY SEASON

5.1 Introduction

Potential water saving through improved irrigation scheduling in the dry season (Chapter 4) provides the opportunity for exploring additional uses of reservoir storage such as supplemental irrigation to bridge dry spells in the rainy season. The reservoir-based irrigation schemes in Sub-Saharan Africa (SSA) which store water, mostly surface runoff, in the rainy season, were originally designed to supply water for dry-season crop irrigation, the livestock sector, fish farming, and domestic use, but not considering supplemental irrigation in the rainy season. However, increasing climate variability calls for exploring the feasibility of supplemental irrigation for crop cultivation in the rainy season (Sanfo et al., 2017). Supplemental irrigation has considerable potential to increase grain yield, particularly if provided during critical stages in the crop growing cycle (booting and grain filling) (Ali and Talukder, 2008). Because of increasing competition for stored water in the dry season, the extra water demand for supplemental irrigation is likely to result in a mismatch between water supply and demand in the reservoir-based irrigation schemes. Thus, the requirement for supplemental irrigation might be satisfied with water saved through increased irrigation efficiency as a result of improving dry-season irrigation scheduling (Chapter 4).

Insufficient water availability, owing to variability in rainfall patterns and frequent dry spells exacerbated by climate change (Cook and Vizy, 2012; Sylla et al., 2016), threatens food security and rural livelihoods in SSA (Sanfo et al., 2017). There, more than 95% of arable land is under rainfed crop production, which contributes 81% to the regional food basket (McCartney and Smakhtin, 2010; Rockström and Barron, 2007). Because of variable rainfall and low-input cultivation (Adwubi et al., 2009; Kranjac-Berisavljevic et al., 2014), grain yields are only from 1 to 2 Mg ha^{-1}, whereas attainable yields range between 4 and 5 Mg ha^{-1} in the region (Dzanku et al., 2015; Rockström and Barron, 2007). Furthermore, risks of crop failure in SSA have increased due to land degradation and soil nutrient depletion (Folberth et al., 2013; Vlek et al., 2017a), signified by negative annual NPK balances with –26 kg ha^{-1} N, –7 kg ha^{-1} P_2O_5, and –23 kg ha^{-1} K_2O as reported in Drechsel et al. (2001). On a continental scale, annual NPK losses averaged 54 kg ha^{-1} (and ranged between 9 kg ha^{-1} in Egypt and 88 kg ha^{-1} in Somalia), resulting in land degradation in more than 40% of Africa's total farmland (Henao and Baanante, 2006; Vlek et al., 2017b). These risks have further reduced the already insufficient financial capacity of farmers to invest in sustainable land management strategies (Rockström and Barron, 2007; Sanfo et al., 2017). However, such strategies are key for optimizing trade-offs between food production and other agro-ecosystem services (Vlek et al., 2017b).

The limited number of studies on supplemental irrigation in SSA has not explored the feasibility of using dry-season water savings in reservoir-based irrigation schemes. For example, Sanfo et al. (2017) investigated the economic value of supplemental irrigation of grain crops using farm ponds of 300 m^3 capacity in south-western Burkina Faso, and reported that in years of low rainfall, supplemental irrigation could be a cost-effective intervention to reduce risks of crop failure and increase farmers' incomes. Fox and Rockström (2003) also assessed the effect of supplemental irrigation, based on 150 m^3 capacity farm ponds, on the grain yield of sorghum in northern Burkina Faso and found that supplemental irrigation alone resulted in approximately 56% increase in grain yield, making it a useful technology to compensate the water shortage in dry spells and shorten the yield gap. Mustapha (2012) studied the water productivity of pearl millet under supplemental irrigation applied at five different crop growth stages in Nigeria, and reported that the supplemental irrigation amount of 84 mm applied at booting and grain filling stages could result in a 69% increase in yields.

In light of the foregoing discussion, this chapter focuses on the assessment of the potential for introducing supplemental irrigation in the rainy season as an adaptation to climate change. To this end, (i) the frequency and duration of dry spells were analysed, (ii) the AquaCrop model was parameterized to render applications for rainfed cropping systems in the UER of Ghana, and (iii) the requirement for supplemental irrigation of maize was determined under different climate scenarios for the rainy season. Maize was chosen over the other rainfed cereal crops because of its relatively high socio-economic relevance in the UER.

5.2 Materials and methods

5.2.1 Study site

The analysis covered the rainy season of 2014 on farms in both the BIS and the VIS sized 0.01–0.31 ha. Waterlogging on the cropping fields was commonly observed after heavy rainfall events owing to the absence of drainage facilities. The principal rainfed cropping systems in the UER are monocropping of rice (*Oryza sativa*) and maize (*Zea mays*), and intercropping of sorghum (*Sorghum bicolar*) with millet (*Pennisetum glaucum*). In particular, Jasmine 85 rice, a local variety of sorghum, an early-maturing variety of millet and Obatanpa maize were cultivated in both irrigation schemes. With the exception of rice, all rainfed crops were planted in rows. The shares of the cropping area in the BIS in the rainy season were 50%, 40%, and 10% for millet-sorghum, rice and maize, respectively, while in the VIS these shares were 34%, 59% and 3%. No supplemental irrigation of the rainfed crops was practiced at the time of this study. The AGB of millet is not shown in this chapter because, as explained below, millet was harvested shortly after the commencement of the study.

The growing cycle of sorghum ranged between 142 and 143 days after planting (DAP), whereas that of millet ranged between 75 and 96 DAP (Appendix 9.11). For rice it was 87–107 DAP, and 84–113 DAP for maize (Appendix 9.11). The rates of agrochemicals applied on the rainfed crops were similar to those for the irrigated crops (see section 4.2.1). On millet-sorghum fields, manure was applied only at plowing, and no mineral fertilizer was applied thereafter. In contrast, rice fields received no manure but were fertilized during the crop growing cycle. On maize fields, manure was applied at plowing, and mineral fertilizer at a later growth stage. Similar to the dry-season irrigated crops, the fertilizers were applied twice in rice and maize fields at 2–3 weeks after planting and later at 4–5 weeks after planting.

5.2.2 Data collection and preparation in the rainy season

The same procedures were followed for the collection of the AquaCrop input data as described in section 4.2.3. For the dry matter determination in cereal crops (millet, sorghum and rice), their grain yields were measured separately from the total AGB.

Crop data could only be collected in 2014 because in the following year technical challenges (sudden resignation of the field assistant) prevented the measurements in both schemes. Because of the late start of the field data collection in 2014, the AGB of maize during the vegetative stage, and that of early millet at both vegetative and reproduction stages was not measured. Of the maize fields, only the BF1 field was monitored in the BIS, as the BF6 maize field was not cropped by the farmer in the 2014 rainy season. Measurement of rice yield components in the BIS BF5 field was not possible due to crop failure resulting from the improper application of herbicides. A summary of all crop growth and yield parameters measured, and details of their measurements are provided in Appendices 17–19.

Only the groundwater data monitored in 2015 were used for the simulations because of the late installation of the groundwater wells in 2014. Furthermore, groundwater measurements could not be carried out between June 3, 2015 and July 15, 2015 owing to a malfunctioning groundwater meter.

Rainfall time series analyses and scenario development

Rainfall data during the years 1998–2014 were obtained for each scheme from the Tropical Rainfall Measuring Mission (TRMM) database. The total annual rainfall and total number and duration of dry spells were determined by the following conditions: (i) onset of rainfall is the beginning of a 10-day period between the second dekad of April and the first dekad of May during which the cumulative rainfall is ≥ 25 mm, and a dry spell ensuing within 30 days from the start of the 10-day period is ≤ 8 days (Amekudzi et al., 2015; Cook and Vizy, 2012), (ii) cessation of rainfall is the last rainfall event between the third dekad of September and the second dekad of October (Amekudzi et al., 2015), (iii) dry spell is two or more consecutive non-rainy days (Kranjac-Berisavljevic et al., 2014), as even a period of two days without rainfall at critical growth stages is detrimental to crop production in savanna environments, particularly during periods of low rainfall, and (iv) frequency of dry spells is the number of dry spells during the rainy season in the particular year under focus.

Additionally, the inter- and intra-seasonal variability of rainfall was expressed in the coefficient of variation based on the annual and monthly rainfall data, respectively:

$$CV = \frac{\sigma}{\mu} * 100 \ [\%] \tag{5.1}$$

where CV is coefficient of variation, σ is the standard deviation, and μ the mean of the rainfall data.

For estimation of the supplemental irrigation requirement for maize, two climate scenarios (wet and dry regimes) were formulated based on rainfall amount and the frequency of dry spells. The first scenario (S1) was a wet year characterized by 20% probability of exceedance, i.e., the likelihood of the occurrence of rainfall ≥ 1057 mm, and by less frequent dry spells (Raes, 2004). The second scenario (S2) was a dry year characterized by 80% probability of rainfall occurrence exceeding 796 mm and by frequent dry spells (Raes, 2004) (Figure 5.1).

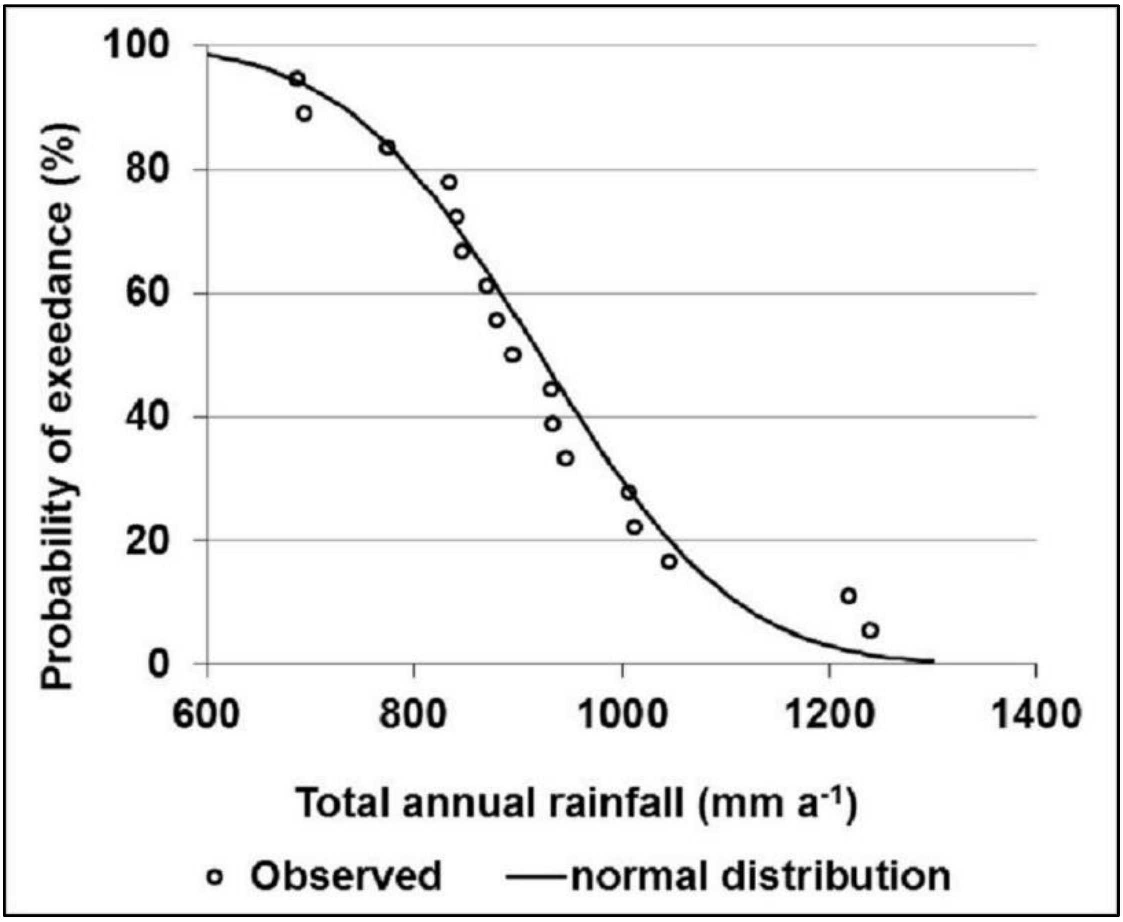

Figure 5.1 Probability plot of the total annual rainfall for the Vea and Bongo irrigation schemes for 1998–2014.

5.2.3 Model parameterization and validation for maize

The 2014 rainy season dataset from the VF1 field was used to parameterize the AquaCrop model for maize, and the 2014 maize dataset from BF1 field was used to validate the model (inter-farm validation). The 2014 maize crop data from BNF1 were found to be unreliable owing to the effects of waterlogging, and thus were excluded from the AquaCrop analysis. The parameters modified in the model were climate, soil characteristics, and agronomic practice (Table 5.1). All the default crop-specific parameters for the maize crop were used. The climate file in daily time steps for the period May 21, 2014 (beginning of the rainfed farming season in 2014) to May 24, 2016 (end of the 2015–2016 dry-season farming) was created using the AquaCrop ET_o file, maximum and minimum temperature file, and a rainfall file.

Table 5.1 Modified parameters and field data used for the parameterization and validation of the AquaCrop model for rainfed maize.

Data required	Model parameterization	Inter-farm model validation
Site conditions		
Cropping field	VF1 (2014)	BF1 (2014)
Crop variety	Obatanpa	Obatanpa
Growing cycle	July 3, 2014 – August 25, 2014	May 24, 2014 – August 14, 2014
Planting method	Direct sowing	Direct sowing
Soil fertility in relation to biomass	Poor	Poor
Initial canopy cover	High canopy cover	High canopy cover
Maximum canopy cover	Fairly covered	Fairly covered
Maximum rooting depth	0.30 m	0.36 m
Harvest index	0.51	0.53
Crop development	In growing degree days	In growing degree days
Field management		
Soil surface cover	No mulch	No mulch
Soil physical characteristics	Field capacity, wilting point, soil moisture, texture, and thickness of soil layer from soil pit 3 in BNF1	Field capacity, wilting point, soil moisture, texture, and thickness of soil layer from soil pit 1 in BF1
Groundwater level	Weekly depth to groundwater table from VF1 well	Weekly depth to groundwater table from BR well
Simulation period	Calendar of growing cycle	Calendar of growing cycle
Field data file	Aboveground dry matter from VF1	Aboveground dry matter from BF1

5.2.4 Supplemental irrigation requirement for maize

Irrigation scheduling was simulated for the maize fields (VF1 and BF1) by selecting the *Net irrigation water requirement* option in AquaCrop, and 50% allowable root zone depletion. The simulation was run to determine the supplemental irrigation requirement under the two aforementioned climate scenarios.

5.3 Results

5.3.1 Reference evapotranspiration in the rainy season

The maximum ET_0 value (7 mm day^{-1} in the BIS; 6.5 mm day^{-1} in the VIS) was recorded in May, whereas the minimum value (1.4 mm day^{-1} in both the BIS and the VIS) was observed in September in both study schemes (Figure 5.2). Similar to the observation in the dry season, the slightly lower ET_0 estimated for the VIS in 2014 could be attributed to a micro-climate created in the area by the Vea reservoir.

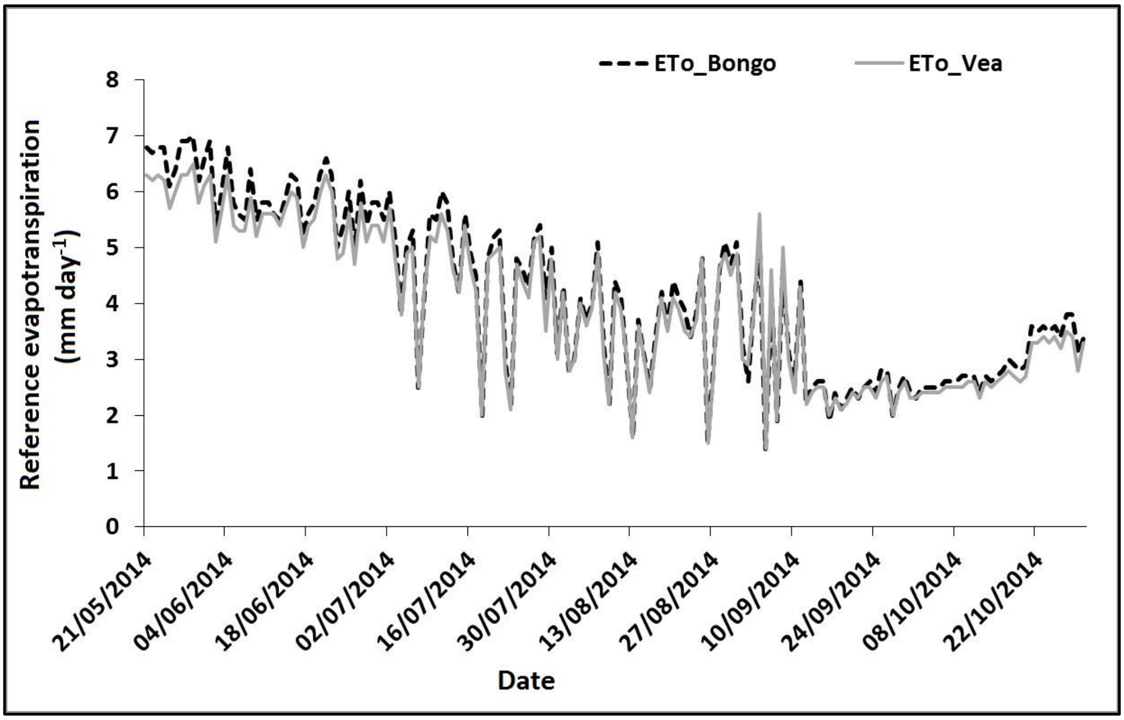

Figure 5.2 Daily reference evapotranspiration in the Bongo and Vea irrigation schemes in the 2014 rainy season

5.3.2 Rainfall and dry spells

Rainfall data analysis revealed a high inter-seasonal variability of rainfall (17%) and frequent dry spells lasting for 2–16 days (Figure 5.3). From 1998 to 2014, the frequency of dry spells in Vea and Bongo ranged between 18 and 28 occurrences. Furthermore, the analysis indicates increasing intra-seasonal rainfall variability in both schemes during the observation period.

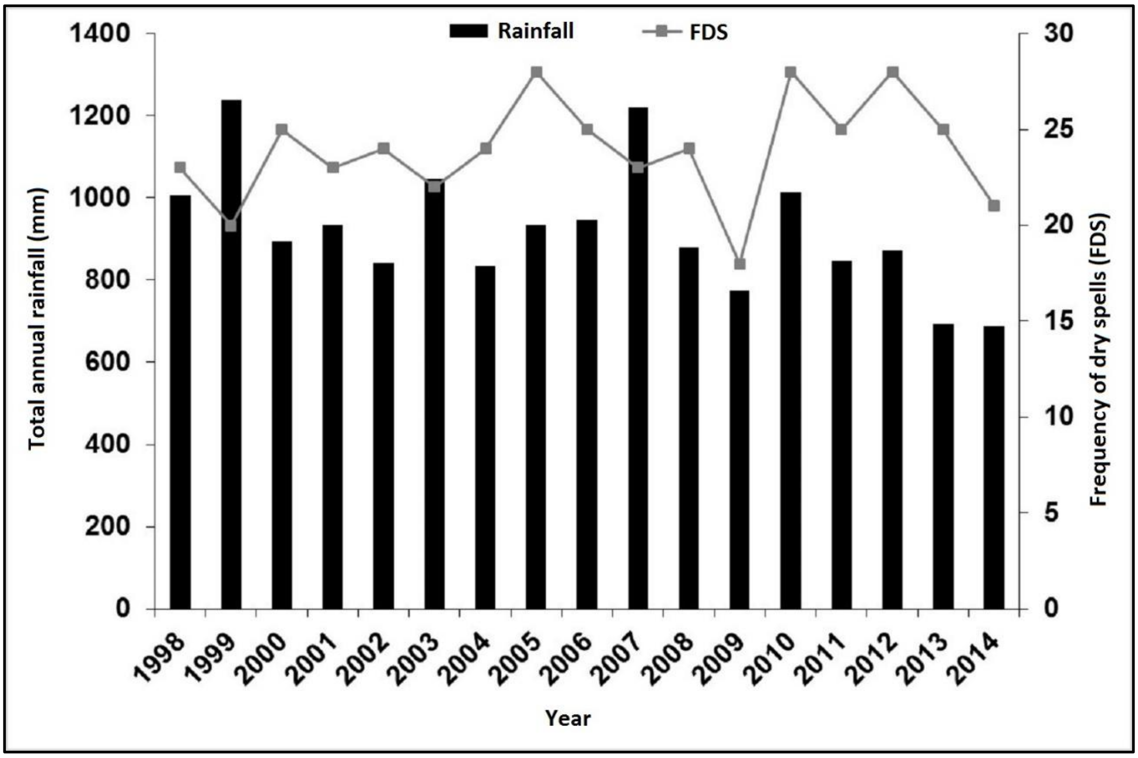

Figure 5.3 Total annual rainfall and frequency of dry spells (FDS) in the Vea and Bongo irrigation schemes during the years 1998–2014.

5.3.3 Crop growth parameters

Maximum rooting depth (RD) and plant density (PD) of maize ranged between 0.3 and 0.36 m, and between 4 and 5 plants m^{-2}, respectively, across the irrigation schemes (Table 5.1). The decline in the maize AGB in VF1 and BNF1 in the VIS was attributed to the effects of late planting (July 3, 2014) and waterlogging, respectively (Figure 5.4a). The RD and PD of sorghum ranged from 0.32 to 0.39 m, and from 16 to 19 plants m^{-2}, respectively, whereas the values for millet ranged between 0.3 and 0.36 m, and between 20 and 49 plants m^{-2}, respectively, across the schemes. The PD of rice in the BIS was in the range of 283-466 plants m^{-2} across the schemes (Table 5.1).

Development of sorghum AGB showed variable trends attributable to the heterogeneity of observed PD on the individual fields or the effect of field-level agronomic practices (Figure 5.4b). In general, rice AGB featured an upward trend through the vegetative and reproduction stages across the schemes (Figure 5.4c).

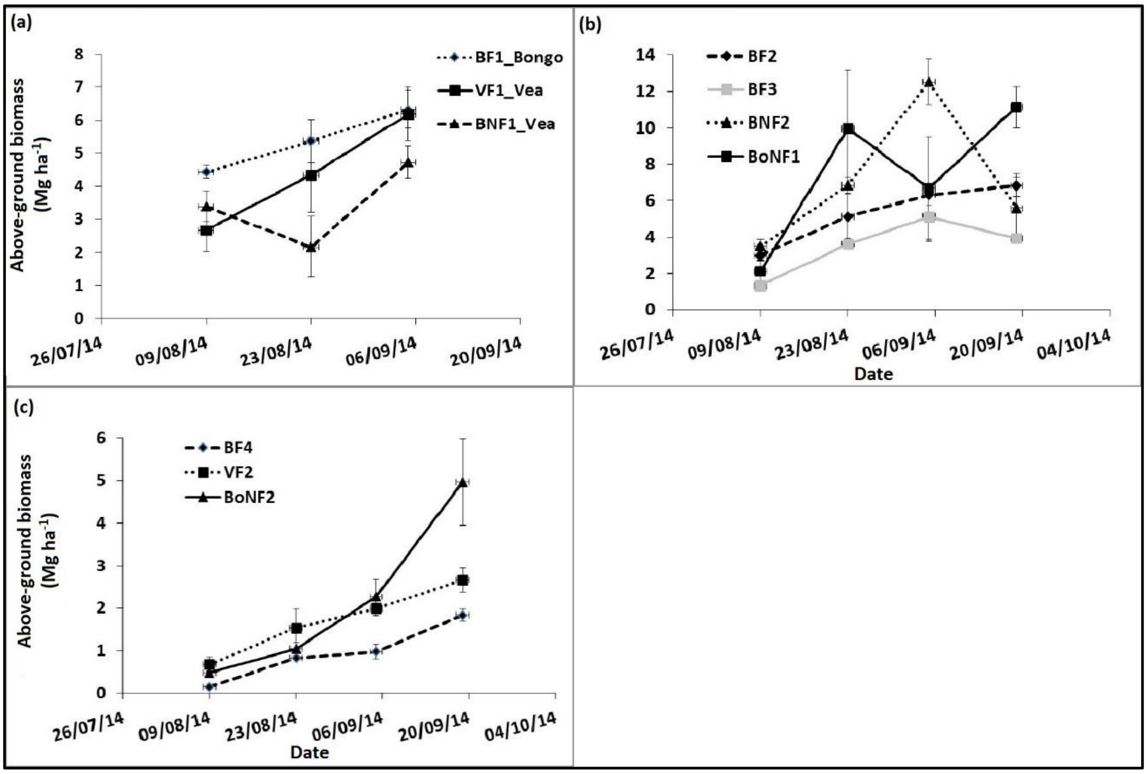

Figure 5.4 Above-ground dry matter of (a) maize, (b) sorghum, and (c) rice in the Bongo and Vea irrigation schemes in the 2014 rainy season.

5.3.4 Crop yield components

In 2014, the maize yield ranged between 1.2 and 2.9 Mg ha^{-1}, and the HI ranged from 0.41 to 0.53 across the irrigation schemes (Table 5.1). The relatively low yield was observed in the BNF1 maize field in the VIS, possibly due to the combined effect of late planting and waterlogging that occurred on this farm. A relatively high maize yield was recorded in the BIS. The yield of sorghum ranged from 0.9 to 1.7 Mg ha^{-1}. The HI of sorghum was remarkably variable among fields, ranging between 0.13 and 0.47. The yield of millet and HI ranged widely between 0.1 and 0.8 Mg ha^{-1}, and between 0.03 and 0.53, respectively. The extremely low yield and HI of millet in BoNF1 field was due to late harvesting by the farmer after most grains had been consumed by birds. The yield of rough rice and HI ranged from 3.3 to 4.3 Mg ha^{-1}, and from 0.43 to 0.54, respectively (Table 5.1). White rice yield measured 1.7–2.8 Mg ha^{-1} across the schemes.

Table 5.1 Crop growth and yield components in the Bongo and Vea irrigation schemes in the rainy season of 2014

Crop type	Field label	Plant density (plants m^{-2})	Maximum rooting depth (m)	Grain yield (Mg ha^{-1})	Harvest index
Bongo irrigation scheme					
Maize	BF1	4.4	0.36	2.9	0.53
Sorghum	BF2	19	0.39	1.7	0.47
Sorghum	BF3	19	0.36	1.0	0.13
Millet	BF2	26	0.36	0.8	0.53
Millet	BF3	47	0.35	0.8	0.48
Rice	BF4	283	n.d.	3.3	0.43
Rice	BF5	349	n.d.	n.d.	n.d.
Vea irrigation scheme					
Maize	VF1	5.5	0.30	2.6	0.51
Maize	BNF1	4.1	0.35	1.2	0.41
Sorghum	BoNF1	16	0.32	1.4	0.11
Sorghum	BNF2	16	0.35	0.9	0.33
Millet	BoNF1	20	0.33	0.1	0.03
Millet	BNF2	49	0.30	0.4	0.15
Rice	VF2	466	n.d.	4.3	0.54
Rice	BoNF2	316	n.d.	2.8	0.51

n.d. = not determined

5.3.5 Groundwater contribution to maize fields

The capillary rise into the root zone of maize simulated by AquaCrop was 43–147 mm in 2014. The daily contribution of capillary rise ranged widely from 0.1–11.7 mm across schemes (Figure 5.5).

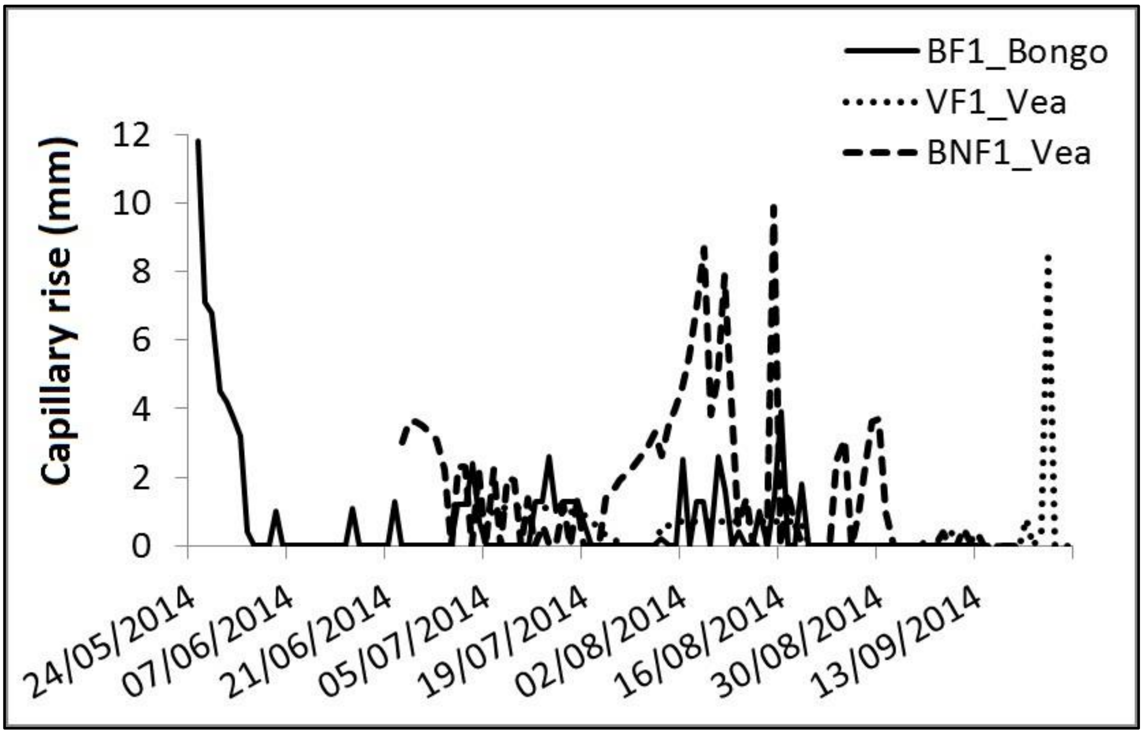

Figure 5.5 Daily capillary rise into the root-zone of maize in the Bongo and Vea irrigation schemes simulated by AquaCrop

5.3.6 Model performance

The model evaluation under maize DM simulation showed a good agreement (EF=0.16-0.78; d=0.6-0.95) and an acceptable error margin (NRMSE=12-13%) (Figure 5.6). However, the low EF (0.16) for maize BF1 field could be due to the fact that biomass data for the vegetative stage of maize was missing for that field.

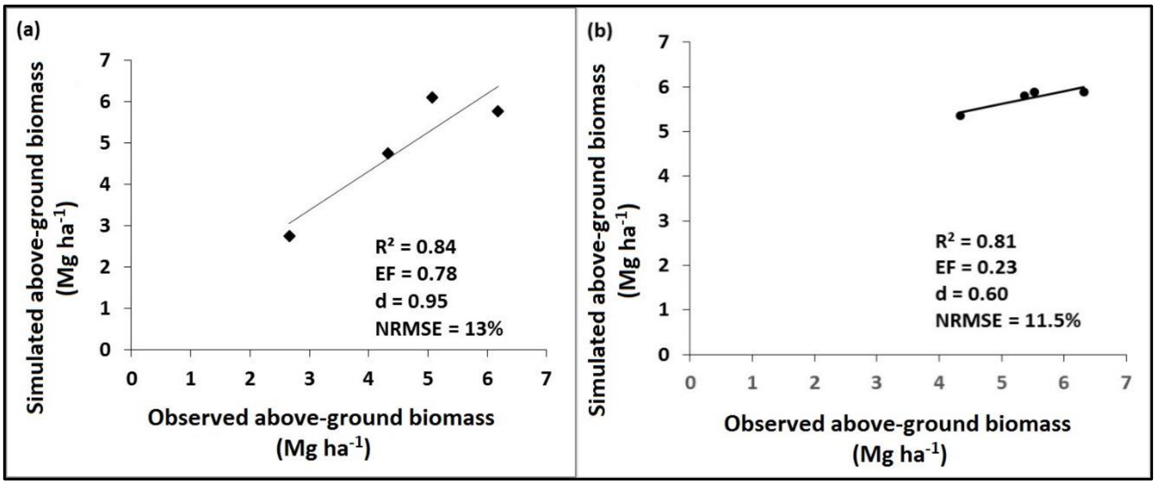

Figure 5.6 Evaluation of AquaCrop-simulated and observed above-ground biomass of maize in the Vea (a) and Bongo irrigation schemes (b)

5.3.7 Scenario analysis of supplemental irrigation requirement for maize

The favorable climate scenario S1 was observed in 1999 when 1,240 mm of rainfall and 20 dry spells were recorded in the rainy season, while the S2 in 2012 showed 871 mm of rainfall and 28 dry spells (the highest frequency of dry spells during the 17-year observation period) (Figure 5.3). Notably, although 2014 recorded the lowest rainfall (687 mm), it was not considered the driest year due to the lower frequency of dry spells (21) compared with 2012. The supplemental irrigation requirement for rainfed maize in S1 was predicted in the range of 88–105 mm (25–29% of NIR of maize). The values predicted for S2, the scenario of low rainfall and frequent dry spells, ranged between 107 and 126 mm (30–35% of NIR of maize) (Figure 5.7). The simulated increase in maize yield under supplemental irrigation ranged between 5 and 14%.

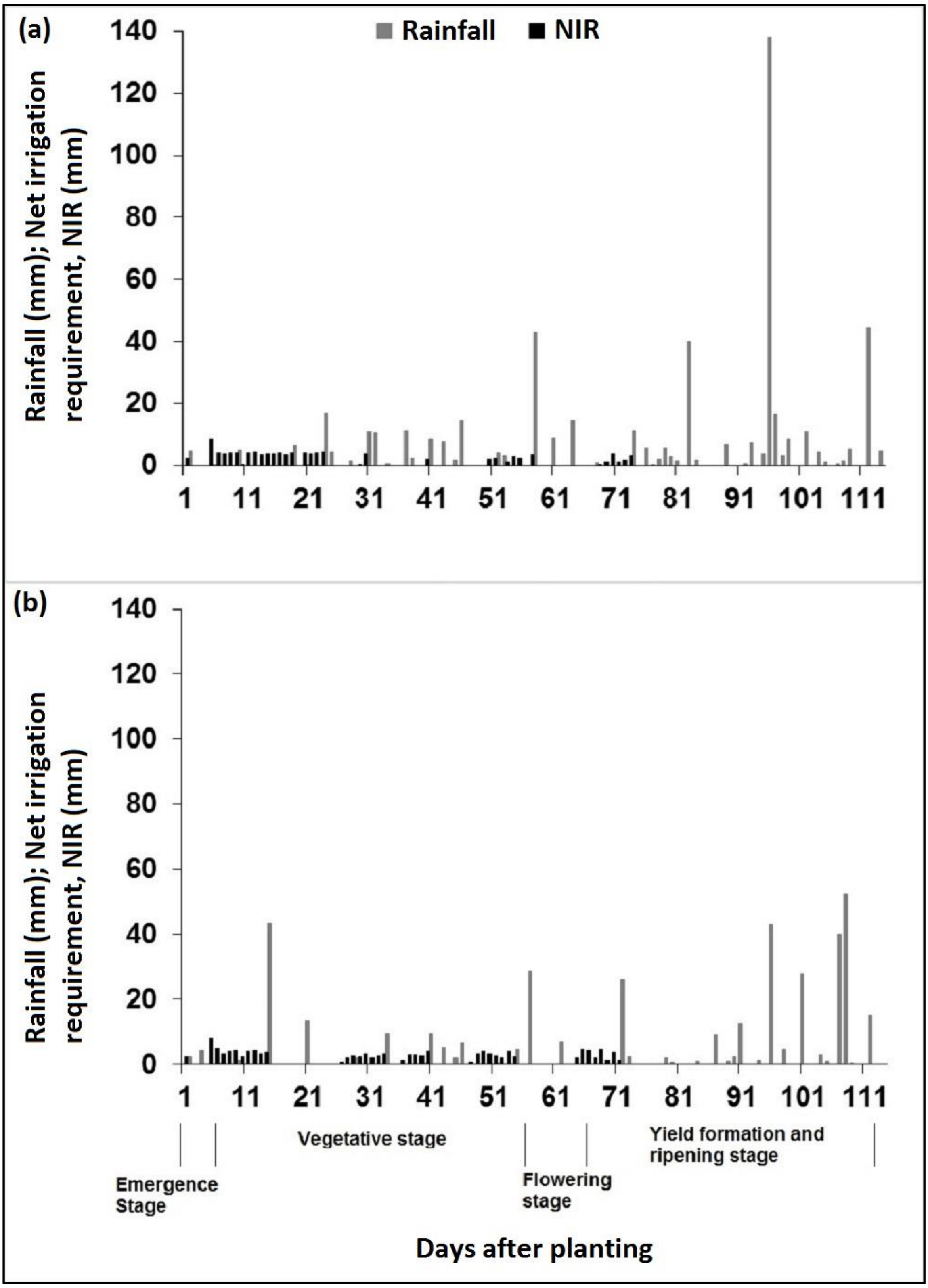

Figure 5.7 Daily rainfall and net irrigation requirement for supplemental irrigation of maize in (a) 1999 wet year and (b) 2012 dry year, as simulated in AquaCrop based on the example of maize BF1 field in the Bongo irrigation scheme.

5.4 Discussion

5.4.1 Crop yields

Late planting and/or waterlogging due to the lack of drainage facilities reduced maize grain yield to only 1.2 Mg ha^{-1} in the affected field in the VIS. This observation confirms late planting as one of the causes of sub-optimal yield levels of rainfed maize, as rainfall typically declines towards the end of the rainy season. Sallah et al. (1997) reported a 30% loss in maize yields due to late planting in northern Ghana. The observed range of maize grain yields in our study (1.2–2.9 Mg ha^{-1}) was similar to that reported for the fertilized Obatanpa maize variety in Ghana (1.3 to 2.7 Mg ha^{-1}; (Srivastava et al., 2017)). The values of Dzanku et al. (2015) for SSA (1.3–1.4 Mg ha^{-1}) were within the lower range of values in this study. However, Sugri et al. (2013) reported the yield potential of the Obatanpa maize variety to be 5.5 Mg ha^{-1} in Ghana.

Although no mineral fertilizer was applied on sorghum-millet fields, the grain yields of sorghum were consistent with those of Steduto et al. (2012), who reported grain yields of 0.6 Mg ha^{-1} and 1–1.5 Mg ha^{-1} under low input practices in Sudan and Burkina Faso, respectively, and 0.5–0.9 Mg ha^{-1} as a common range in Africa. Breman et al. (2001), however, reported values less than 1 Mg ha^{-1} in Mali due to extremely low soil fertility. The observed HI of sorghum, similar to the findings of Steduto et al. (2012), was remarkably variable between fields and ranged from 0.1 to 0.5. The observed grain yields of early-maturing millet are consistent with values (0.5–0.8 Mg ha^{-1}) reported by Breman et al. (2001) in Mali but on average (0.53 Mg ha^{-1}) are slightly higher than the average yield in semi-arid regions (0.5 Mg ha^{-1}; de Rouw, 2004).

The observed grain yield of rough rice was lower than the average yield (4–5 Mg ha^{-1}) of fertilized lowland rainfed rice reported by Steduto et al. (2012). In contrast, the observed HI of rice was higher than 0.35 reported by Steduto et al. (2012).

Variations in practices of soil nutrient management and often insufficient applications of fertilizer in the examined fields could have contributed to the variability in yields. Folberth et al. (2013) emphasized that even modest additions of N and P fertilizer might double maize production in most of SSA. Insufficient application of mineral fertilizer is common due to the high cost (Folberth et al., 2013; Srivastava et al., 2017).

5.4.2 Feasibility of supplemental irrigation

The observed temporal variability in rainfall across the irrigation schemes highlights the urgent need for water management strategies to reduce the risks in rainfed crop production. The intra-seasonal variability of rainfall revealed by the frequency of dry spells was found to influence water demand for crop growth more strongly than the total rainfall over the growing season. In the VIS, for example, the supplemental irrigation requirement for maize simulated with the 2014 rainfall was 29 mm, whereas in the wetter year 2012, this value was 107 mm due to the higher frequency of dry spells (28). Similarly, although 1999 was recognized as the wet year for S1 according to the aforementioned criteria, the simulated NIR for supplemental irrigation of maize was 88 mm due to the higher intra-seasonal variability (69%) in that year than in 2014 (64%). Furthermore, the temporal rainfall variability was consistent with the findings of Fox and Rockström (2003), who observed high rainfall variability of > 25% during the years 1923–1995 in the Sahelian region. Kranjac-Berisavljevic et al. (2014) estimated dry spells lasting for 2–13 days in the Savanna agro-ecological zone of Ghana.

The supplemental irrigation requirement for maize estimated by AquaCrop (29–126 mm) was within the range of the values determined by Rockström and Barron (2007) in semi-arid Mwala in Kenya (20–240 mm). Overall, considering only the crop irrigation sector, the quantity of water saved through improved irrigation scheduling of dry-season tomato (as discussed in section 4.4.3) is largely sufficient to accommodate supplemental irrigation of maize in the rainy season, and thus as an adaptation to the rainfall variability and recurrent dry spells. Even for the dry climate scenario of low rainfall coupled with frequent dry spells, about 126 mm of water at field level would be required for the supplemental irrigation of maize during the rainy season.

Furthermore, the simulated yield increase in maize under supplemental irrigation would offer an incentive for managers of the Bongo and Vea schemes to explore this strategy. It should be noted that due to the reservoir losses through evaporation and seepage, some of the water saved in the dry season might not be available for supplemental irrigation in the rainy season or the latter can compromise water availability for the dry-season crop production. Therefore, an effective year-round irrigation schedule considering the water availability of the entire scheme is required.

5.5 Conclusions

High temporal variability in rainfall and frequent dry spells lasting for 2–16 days are common in the UER, requiring adaptive measures to enhance rainfed crop production. The supplemental irrigation requirement for maize under the dry climate scenario of low rainfall and frequent dry spells was estimated between 107 and 126 mm, whereas for periods of high rainfall and rare dry spells, between 88 and 105 mm would be required. These demands can be satisfied via improved irrigation scheduling for dry-season tomato that can potentially save 130–1,325 mm of water, which would otherwise be lost through percolation and evaporation. Maize yield increment in the range of 5–14% is predicted under supplemental irrigation.

Given the sub-optimal nutrient management practices observed across the study sites, further research should investigate the impact of soil fertility on water productivity in assessing the potential of these management practices combined for improving crop yields, and the year-round food security in Sub-Saharan Africa.

6 SCENARIO-BASED, FUNCTIONAL ASSESSMENT OF MULTI-PURPOSE RESERVOIR-BASED IRRIGATION SCHEMES UNDER CLIMATE VARIABILITY

6.1 Introduction

After assessing the irrigation performance (Chapter 3), and developing an irrigation schedule to tackle the overarching problem of over-irrigation in the reservoir-based irrigation schemes (Chapter 4) as well as exploring the use of the potential water saving in the dry season for supplemental irrigation in the rainy season (Chapter 5), comprehensive information about the current state of the reservoir-based irrigation schemes in the UER and possible interventions regarding some of the revealed problems has been acquired. In particular, the water savings in the dry season through appropriate and effective irrigation scheduling provide an opportunity for supplemental irrigation in the rainy season, thus ensuring a year-round water management strategy rather than the dry-season-based water management (Sekyi-Annan et al., 2018a). It is thus worthwhile at this juncture to capitalize on this information to further conduct a functional assessment of these schemes to satisfy competing water demands under climate variability. The assessment of the reservoir performance (Chapter 3) is based on the existing water storage in the reservoirs, however the assessment under climate variability presented in this chapter went a step further to examine the hydrological characteristics of the catchment upstream generating runoff into the reservoir.

Competition for water resources in reservoir-based irrigation schemes in Sub-Saharan Africa (SSA) is on the rise owing to population growth, climate change and multiple water users, posing thus imminent constraints on environment, livelihoods, development and economic growth (Adwubi et al., 2009; Fowe et al., 2015). Small- and medium-scale reservoirs have been constructed on streams (Fowe et al., 2015) and mostly in valleys (Adwubi et al., 2009) all over SSA to provide a year-round water availability for competing water users including crop irrigation, livestock, fishery and domestic use (Acheampong et al., 2014; Chapter 3). Especially in regions with distinct rainy and dry seasons as in northern Ghana, small- and medium-size reservoirs were considered as a promising water management intervention and thus introduced (Venot et al., 2012). High rainfall intensity combined with low infiltration rate of soils in the reservoir catchments in northern Ghana favors surface runoff generation from rainfall (Adwubi et al., 2009; Liebe et al., 2005). Consequently, the collection of runoff during the rainy season for usage in dry periods is appropriate under the hydro-geo-climatic conditions in semi-arid regions like the UER (Fowe et al., 2015), where mean annual rainfall is approximately 970 mm and the mean annual ET_0 is about double the rainfall. In such a data-scarce environment as the UER and most parts of SSA (Näschen et al., 2018), water inflows to and outflows from the reservoirs in several locations are either ungauged or poorly monitored making hydrological studies on the water storage infrastructure a challenging task (Conway et al., 2009; Fowe et al., 2015).

Current operations of reservoir-based irrigation schemes in the SSA need to take into account that most of the reservoirs have lost varying percentages of their storage capacity due to siltation as also observed in the BIS (Chapter 3). According to Adwubi et al. (2009), the increasing farming activities in the catchment areas combined with the aforementioned high rainfall intensity results in reservoir siltation in the UER. The loss of the storage capacity of reservoirs limits water sufficiency for the multiple water uses in the region including supplemental irrigation.

Furthermore, the sectoral approach to water management such as that currently practiced in Ghana amid multiple users leads to inequitable water allocations and related conflicts during periods of water shortage (Chapter 3). Most often, conflicts occur between irrigators, who tend to use most of the water (de Bruin et al., 2015), and the other competing users. Especially in periods of water scarcity, crop-irrigation demand often encroaches on the other multiple water demands (e.g. livestock needs) even though livestock water demand is perceived to have the highest priority in small-scale schemes, where boreholes have been constructed to satisfy the drinking water needs (Acheampong et al., 2014).

Increased spatio-temporal variability in rainfall distribution in most parts of SSA has affected reservoir refilling in the rainy season (Boko et al., 2007; Sylla et al., 2016). The adoption of an integrated approach for reservoir operation by considering the current (Chapter 3; Sekyi-Annan et al., 2018b) and future demands of all multiple sectors is particularly important to enhance the equitable and fair allocation of the scarce water resources (Höllermann et al., 2010; Venot et al., 2012). An integrated approach could forestall water-related conflicts, promote social cohesion among the water users, and facilitate the achievement of the overall goal of food security and livelihood improvement (Kramer, 2004). This will enhance the resilience of the water users to climate change and variability.

Assessments based on the integrated systems approach accounting for competing water demands in a changing environment remain rare in published research. For instance, García-Bolaños et al. (2011) diagnosed the performance of 22 small- and medium-scale reservoir-based irrigation schemes along the banks of the Senegal River in Mauritania with the sole focus on irrigated rice, thus excluding fish and livestock farming, which are however the important competitors for water. Similarly, only irrigation needs were accounted for by the performance evaluation of small-scale schemes in the Upper Volta Basin in Ghana and Burkina Faso (Poussin et al. 2015) and in the comparative performance analysis in the Ouémé and Zou reservoir-based irrigation schemes in Benin (Djagba et al. 2014). Furthermore, Asres (2016) assessed the performance of a multi-purpose irrigation scheme in Ethiopia but focused on the field-level crop irrigation demands only.

However, a number of studies in SSA applied the model-based approach to performance assessment of multi-purpose reservoir-based irrigation schemes. Badou et al. (2018) quantified the climate change impact on future green water and blue water resources in four sub-basins of the Beninese part of the Niger River Basin under two greenhouse gas emissions scenarios, and found that green water will increase in all of the four studied sub-basins, while blue water will only increase in one sub-basin. However, they reported larger uncertainty for the quantification of blue water than of green water. Adgolign et al. (2016) modeled the vulnerability to water shortages of areas within the Didessa sub-basin in western Ethiopia under scenarios of increasing domestic water demand, increasing irrigation area, and increasing hydropower capacity using the Water Evaluation and Planning System (WEAP) model, and predicted a reduction of 10.3% in the total annual flow of Didessa River by 2050. In particular, the reservoir-based irrigation schemes in the Dabena, Anger and Upper Didessa watersheds were forecast to record unmet water demands in 2050. The challenge of incomplete streamflow data was overcome in their study by supplementing those data with streamflow simulated in the Soil and Water Assessment Tool (SWAT) model. Höllermann et al. (2010) analyzed the future water situation of Benin under different scenarios of climate change and socio-economic development until 2025 using WEAP, and showed a potential increasing pressure on Benin's water resources which would lead to greater competition for surface water, as climate change could decrease inflows and groundwater recharge. Constraints with the input data and uncertainties about the model were the main challenges faced in their analysis. However, WEAP outputs revealed hot spots for action, and thus offered a foundation for future water resource management in Benin. In the Upper Ewaso Ng'iro north basin in Kenya, Mutiga et al. (2010) applied WEAP in reconciling the water requirements for various competing sectors and the available water resources. They revealed that high irrigation water demand was the principal cause of excessive water withdrawal in the upstream catchments in particular resulting in water shortages downstream and consequently water-related conflicts.

Water-related conflicts in the reservoir-based irrigation schemes and the lack of integrated assessments to reconcile the competing water demands and the available water resources stipulate the urgent need to re-think the water management in reservoir-based irrigation schemes in the UER by adopting the integrated systems approach. This chapter presents the results of this evaluation for the VIS and the BIS in the UER considering (i) the entire hydrological system (or unit) consisting of the basin generating the surface and subsurface runoff, the water reservoir, the conveyance and drainage network, cropping fields, as well as the other competing water users such as livestock, fishery and domestic demands, and (ii) current season-related water allocation rules into a year-round water allocation strategy, and its evolution over time in the face of climate variability using the WEAP model. In this respect, a scenario-based analysis should be furthermore conducted to determine future options for the reservoir-based whole-scheme operations under the increasing water scarcity. To this end, simulation results including discharge, water demand and unmet demands under the different scenarios were analyzed in order to understand how water demand and supply evolved over time, the impact of rainfall variability, and the magnitude of potential shortages in water supply in times of water scarcity.

6.2 Materials and methods

6.2.1 Study site

This assessment covered the 2014–2016 rainy and dry seasons in the BIS and the VIS (Chapter 2). The relevant technical characteristics of the irrigation schemes are summarized in Table 6.1. The current volume-elevation curve of the Bongo reservoir developed during the fieldwork estimates the elevation of the spillway at 231 m and that of the top of the dead storage at 226.6 m. In the case of the Vea reservoir, the design volume-elevation curve used for the analysis measured the elevation of the spillway and top of the dead storage as 189 m and 181.5 m, respectively. The volume-elevation curve for the Vea reservoir was developed after the construction of the dam about four decades ago, hence the current situation is likely to differ from the designed due to sediment accumulation in the reservoir (Adwubi et al., 2009).

Table 6.1 Technical characteristics of the Bongo and Vea dams and reservoirs

Technical characteristics	Bongo dam	Vea dam
Length of dam wall (m)	625	1,585
Maximum depth (m)	5.5	13.4
Flooded area at full supply level (ha)	20.7	380
Storage capacity (million m^3)	0.433	17.27
Live (useful) storage (million m^3)	0.43	16
Dead storage (million m^3)	0.003	1.27

The design gross irrigable area of the VIS is 1197 ha. About 70% (850 ha) has been developed for cultivation (Chapter 3), meaning that the remaining 30% of the area could be developed to increase the irrigation potential of the scheme. Nonetheless, data available from the monitored locations are woefully sparse and in September 2013, streamflow into and outflows from the Vea reservoir were not monitored. In the BIS, data on discharge into the reservoir were unavailable due to the ungauged Bongo catchment.

The Vea reservoir supplies water to the Ghana Water Company limited (GWCL) for treatment and onward distribution to the Bolgatanga municipality, which has a population of 131,550 (GSS, 2012). The townspeople in both Vea and Bongo, however, depend on boreholes for their domestic water needs. In the irrigable area of the VIS, 22 fish ponds with surface areas ranging between 0.1 and 0.5 ha, and an average depth of 1.5 m fed by water from the Vea reservoir were constructed for fish farming, whereas fishery in the BIS is done directly in the Bongo reservoir (Chapter 3).

6.2.2 Description of the WEAP model

The WEAP model, developed by the Stockholm Environment Institute, Sweden, has produced outputs which have assisted water managers and decision makers in balancing water supply generated through catchment-scale hydrologic processes, and spatio-temporally variable water demands of multiple users having different water allocation priorities and water supply preferences (Shirke et al., 2012). By assessing current and future water demand and supply management, WEAP has shown to be an effective forecasting and policy analysis tool in SSA including in Benin (Höllermann et al., 2010; Mutiga et al., 2010), Kenya (Mutiga et al., 2010) and Ethiopia (Adgolign et al., 2016). Furthermore, the model can be used as a discussion tool to work out water management options jointly with water users. Because the structure of the input data and the level of detail (either aggregated or disaggregated), time steps (daily, monthly etc.), and spatial extent can be tailored to specific local conditions, WEAP is adaptable and applicable to a wide range of contexts and spatial scales such as scheme scale, sub-basin scale and basin scale (Sieber and Purkey, 2015). In WEAP simulations, the demand side of the water balance equation is put on the same scale as the supply side, thus making it a better choice than most hydrological simulation models which are usually supply oriented (Sieber and Purkey, 2015).

6.2.3 Parameterization of WEAP

The WEAP model was configured and parameterized with the field data (Figure 6.1) collected during May 2014 – May 2015. A current accounts year, which is the baseline year depicting the prevailing situation in the scheme and has the most complete datasets for the simulations, was created and parameterized following Sieber and Purkey (2015).

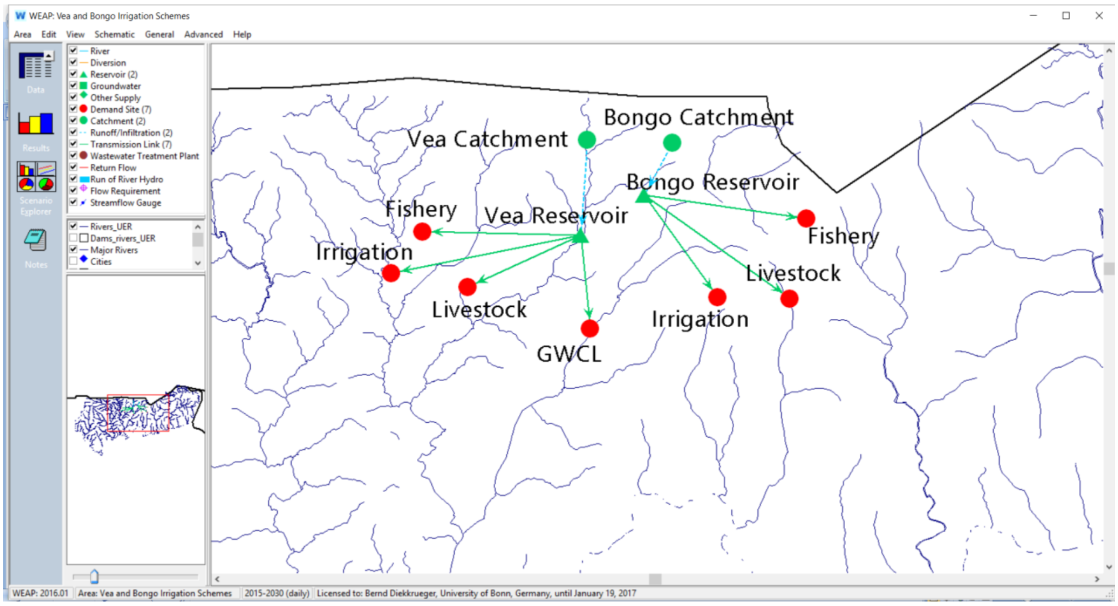

Figure 6.1 Screenshot of the water supply and demand in the Bongo and Vea irrigation schemes

General parameters

The current accounts year was set to 2015 (May 21, 2014 to May 20, 2015) and the last year of the scenarios to 2030. The latter was set as the last year since it is targeted by the Sustainable Development Goals (SDGs) as well as by the Ghana National Climate Change Policy to reduce vulnerability in the savanna agro-ecological zone of the country (Barakat et al., 2015; MESTI, 2013). The simulations were conducted in daily time steps. Monthly time steps were previously used in several hydrological studies conducted in the SSA (e.g. Fowe et al. (2015); Höllermann et al. (2010); Ofosu et al. (2010), and Mutiga et al. (2010)), but here the daily temporal resolution was applied to ascertain the potential real-time changes in the catchment hydrology regarding runoff generation and reservoir refilling, variations in demand and supply, and the resultant impact on the reservoir's operation. Furthermore, the daily time step applied for the analysis was relevant due to the rather small size of the Bongo and Vea catchments which could respond quickly to rainfall, and the fact that irrigation schedules use daily time steps.

Water resources and supply

The rainfall-runoff version of the simplified coefficient method was used in the estimation of discharge from the Bongo and Vea catchments (Sieber and Purkey, 2015). The aforementioned method determines the fraction of rainfall lost through crop-specific ET using crop coefficients, and the remainder of the rainfall is simulated as discharge to the reservoir. This method was selected due to its suitability for the catchment characteristics and the moderate data requirement as observed by Mutiga et al. (2010). The 2014 rainfall data were applied for simulations in the current accounts year 2014–2015, whereas the long-term (1998–2014) average rainfall data was applied for the scenario analyses. Potential evapotranspiration (ET_0) for the current accounts year was computed using the Penman–Monteith equation (Allen et al., 1998) (Eq. 4.1).

The crop coefficients (K_c) of maize were used (Allen et al., 1998; Sieber and Purkey, 2015), as maize was the dominant rainfed crop. Because WEAP overestimated the discharge in both catchments in the current accounts year, the modeled discharge data were adapted for the respective schemes by manually dividing the rainfall-runoff coefficients with a factor until there was a good agreement between the simulated and the observed storage changes in the reservoir for each scheme (Mutiga et al., 2010; Ofosu, 2011). Specifically, the daily surface discharges modeled in WEAP were divided by an average factor (8 for Vea; 7 for Bongo) such that the simulated daily storage data were similar to the daily observed storage. In the BIS, daily observed storage data recorded in 2014–2015 were available for December 9, 2014 – March 11, 2015 only, and thus this period was focused on the runoff data analysis.

Water demand for the multiple users

Three demand sites (water users) including livestock, fishery, and irrigation were identified in the BIS, and in addition the GWCL in the VIS. Furthermore, supplemental irrigation of maize in the rainy season was added to the traditional demand sites in the schemes under the supplemental irrigation scenario.

The gross water demands (GWD, $m^3\ a^{-1}$) for the respective demand sites were used (Table 2). The Annual Water Use Rate (AWUR; $m^3\ ha^{-1}$ for irrigation, $m^3\ head^{-1}$ for livestock, $m^3\ pond^{-1}$ for fishery, $m^3\ unit^{-1}$ for GWCL) was calculated as follows:

$$AWUR = \frac{GWD}{AAL} \tag{6.1}$$

where the Annual Activity Level (AAL; ha, head, pond or unit) is the factor driving water demand for the multiple water users including cropping area (ha), livestock population (head), number of fishponds (pond) and water treatment plants (unit).

The analysis of the water withdrawal data by the GWCL revealed a fixed volume of water abstracted over the period 2013–2016 (Appendix 9.10). Hence, it is the capacity of the water treatment plant and not the human population that is likely to limit the water demand, as has been mostly observed (Adgolign et al., 2016; Mutiga et al., 2010). The AWUR for livestock was disaggregated for the different species, namely cattle, donkeys, sheep and goats. The irrigation AWUR was specifically computed for tomato, leafy vegetables and rice according to their share in the total irrigable area in the respective irrigation scheme (Tables 6.2 and 6.3). Although fish farming practiced directly in the Bongo reservoir is a non-consumptive water user, it was still considered a demand site in the simulation in order to determine the extent to which other users (e.g. livestock) might compete with fishery during periods of water scarcity. The fishery water demand in the VIS (FWD; $m^3\ a^{-1}$) was determined as follows:

$$FWD = AET_0 \tag{6.2}$$

where *A* is surface area of fishpond at full supply level (m^2), and ET_0 is average potential evapotranspiration (m).

Subsequently, the FWD in the VIS in 2014–2015 varied from one fishpond to another (900–7,500 m^3) due to size variations between 600 and 5,000 m^2, and an average ET_0 of 1.5 m (Appendix 9.9). However, a mean value of the FWD was applied in the analysis (Table 6.3). In the BIS, the dead storage of the reservoir was assumed to satisfy FWD (section 3.2.5).

The GWD for the supplemental irrigation of maize was calculated as the ratio of the mean net irrigation water demand of 107 mm per growing season to the system efficiency of 52% (Chapter 3). The entire irrigable area was assumed to be cultivated with maize only. Hence, the AWUR for the supplemental irrigation scenario was estimated by dividing the GWD by the total area under maize cultivation (12.05 ha for Bongo, 400 ha for Vea) representing a 100% share of the irrigable area in both schemes.

Table 6.2 Disaggregated water demands for the current accounts year 2015 in the Bongo irrigation scheme. GWCL: Ghana Water Company Limited

Demand site	Annual activity level	Annual water use rate
Livestock	11,600 heads	
Cattle	21.6%	5.7 m^3 $head^{-1}$
Donkeys	6.5%	3.4 m^3 $head^{-1}$
Sheep	33.2%	1.1 m^3 $head^{-1}$
Goats	38.8%	0.9 m^3 $head^{-1}$
Irrigation	12.05 ha	
Tomato	40%	9,166.4 m^3 ha^{-1}
Leafy vegetables	55%	4,182.7 m^3 ha^{-1}
Rice	5%	5,556.8 m^3 ha^{-1}
Maize (supplemental irrigation scenario)	100%	2,058 m^3 ha^{-1}
Fishery	1 pond (dead storage)	2,642 m^3

The daily share (variation) in annual water use rate for the demand site (Table 6.4) was estimated based on the period of the year in which water was used for the respective purpose, i.e., for each day within the period of interest, a particular share of the total water demand was assigned, and "0" was assigned to the remaining part of the year. Such was applicable to irrigation, livestock and fishery, which were practiced only in the dry season, and for supplemental irrigation which only occurred in the rainy season. In the rainy season, the livestock mainly depend on rainwater collected in ponds located in the neighborhood rather than on the reservoir water (section 3.2.5). Similarly, fishery is not practiced in the rainy season in both irrigation schemes, and thus there is no diversion of water into the fishponds in the VIS during this season.

Table 6.3 Disaggregated annual water demands for the current accounts year in the Vea irrigation scheme. GWCL: Ghana Water Company Limited.

Demand site	Annual activity level	Annual water use rate
GWCL	1 unit	2,103,031 m^3 $unit^{-1}$
Livestock	22,070 heads	
Cattle	27.5%	5.7 m^3 $head^{-1}$
Donkeys	0.4%	3.4 m^3 $head^{-1}$
Sheep	30.4%	1.1 m^3 $head^{-1}$
Goats	41.7%	1.1 m^3 $head^{-1}$
Irrigation	400 ha	
Tomato	48%	5,995 m^3 ha^{-1}
Leafy vegetables	12%	4,736.8 m^3 ha^{-1}
Rice	37%	4,132.4 m^3 ha^{-1}
Maize (Supplemental irrigation scenario)	100%	2,058 m^3 ha^{-1}
Fishery	22 ponds	4,336.4 m^3 $pond^{-1}$

Table 6.4 Daily share of the annual water use rate for the different demand sites

Demand site	Period of the year	Share of annual water use rate (%)
Livestock	September 11 – April 11	0.47
Irrigation	December 14 – April 11	0.84
Fishery	December 14 – April 11	0.84
Supplemental irrigation	May 21 – October 30	0.61

Water demand priorities were set for the different demand sites based on the perception of the ICOUR water manager in the VIS, and the WUA in the BIS (Table 6.5). The index 1 represents the highest priority and “2” the lowest priority in Bongo, and “3” the lowest priority in Vea. During a period of water shortage, the highest priority demand is met as fully as possible by the model before the lower priority demand is supplied depending on the available water. Furthermore, in instances when the water users have the same demand priorities, WEAP shares the available water equally between them in terms of water quantities (Sieber and Purkey, 2015).

Table 6.5 Demand priorities for water users in the Vea and Bongo irrigation schemes

Demand site	Priority	
	Vea	Bongo
Ghana Water Company Limited	1	n.a.
Livestock	2	1
Fishery	3	2
Irrigation	3	2

n.a. = not applicable

Hydrology

The Water Year Method, which forecasts inflows to the reservoir by varying the discharge data in the current accounts year based on user-defined variability and adjustment factors, was used to estimate inflows for the entire simulation period (Sieber and Purkey, 2015). In particular, the generated inflow data based on the long-term average rainfall served as the baseline data for the simulations over the 2015–2030 period coupled with the adjustment factors. The adjustment factors were estimated using the probabilities of exceedance of rainfall determined from historical rainfall data (1998–2014) accessed from the Tropical Rainfall Measuring Mission (TRMM) database for Bongo and Vea (Figure 6.4). These probabilities of exceedance were classified into different climate regimes, i.e., water year types: 10% (very wet), 20% (wet), 50% (normal), 80% (dry) and 90% (very dry) according to Raes (2004). Subsequently, the adjustment factor for a particular water year was determined as the ratio of the rainfall in that year to the rainfall in a normal year (Table 6.6). Hence, these adjustment factors express the amount of inflows to the reservoir in a particular water year relative to that of a year with normal rainfall. Ofosu (2011) applied a similar approach in the White Volta Basin, where he grouped a long-term rainfall dataset into the different climate regimes and then estimated the adjustment factors as the mean rainfall for each category to the long-term mean (Table 6.6).

The water year type for the 2014–2015 current account year was specified as a ‘normal year’ for both Bongo and Vea based on the long-term average annual rainfall of 921 mm (Figure 5.1). The sequence of the water year types for the rainfall variability scenario over the simulation period was randomly designed (Table 6.7). The water year type for the reference scenario corresponded to that of the current accounts year in both schemes for the whole simulation period. The remaining scenarios inherited the sequence from their ''parent'' scenarios. In the scenario tree, a former scenario is “parent” to the latter, and thus influences it.

Table 6.6 Water-year types and adjustment factors for estimating inflows to Bongo and Vea reservoirs

Water-Year Type	Factors	
	Bongo and Vea	White Volta Basin*
Very dry	0.79	0.76
Dry	0.87	0.89
Normal	1	1
Wet	1.15	1.09
Very wet	1.24	1.27

**Ofosu (2011)*

Table 6.7 Sequence of climate regimes for the rainfall variability scenario

Year	Climate regime	Year	Climate regime
2015	Normal	2023	Normal
2016	Very wet	2024	Dry
2017	Very wet	2025	Very dry
2018	Very dry	2026	Very dry
2019	Dry	2027	Dry
2020	Normal	2028	Normal
2021	Wet	2029	Wet
2022	Very dry	2030	Very dry

Scenarios and assumptions

Five scenarios focusing on potential changes in the physical condition and size of the irrigation scheme, water availability as influenced by variable rainfall and management decision such as the introduction of supplemental irrigation in the rainy season as well as relevant assumptions based on field observations (e.g., increasing livestock population and cropping area) were formulated for the simulations as follows:

Reference scenario

The reference scenario is a business-as-usual scenario in which the status quo is maintained with a yearly livestock population growth of 10%. The 10% growth is the national growth rate of livestock populations for projections adopted by the Animal Production Unit of the Veterinary Services Department in MOFA of Ghana. This scenario, which serves as a baseline for the other scenarios over the 2015–2030 simulation period, provides insights into how the reservoir performs in the future if no improvement of the system occurs.

System efficiency improvement scenario

The system efficiency improvement scenario simulates the impact of demand management strategies, such as water loss reduction through the repair of the water conveyance and distribution infrastructure, and the adoption of an improved irrigation scheduling, on water availability for the competing water demands. Hence, for the simulation, the overall irrigation system efficiency was assumed to improve by 10% in order to enhance water saving, as a potential exists to increase system efficiency in the Bongo and Vea irrigation schemes by about 36% (Chapter 3). Analysis of the simulation results under this scenario sheds light on the sufficiency of the water saved in the dry season for the purpose of supplemental irrigation in the rainy season.

Irrigable area expansion scenario

The irrigable area expansion scenario gives an idea of the ability of the reservoir-based irrigation scheme to balance water supply and demand as the cropping area gradually expands over the simulation period while the current water management practices as well as the condition of the water delivery infrastructure remain unchanged. Hence, this scenario develops from the reference scenario.

In the VIS, the current cropping area of 400 ha is assumed to increase by 30 ha per annum (7.5%) over the simulation period until the entire (potential) irrigable area of

850 ha is cultivated. In the BIS however, the original share of land under tomato cultivation was assumed to increase by 50% (from 40 to 60%) across the simulation period by the reduction of the area cropped with leafy vegetables by about 36%, as there was no opportunity to expand the total irrigable area of the scheme (12.05 ha). This assumption for the BIS aimed at assessing the potential limit of water demand in the dry season when the production of the water-intensive tomato crop increased under the prevailing conditions of the scheme.

Rainfall variability scenario

The rainfall variability scenario ascertains the impact of increased rainfall variability on reservoir storage and the scheme's resilience to meet the gross water demands of the multiple users of the reservoir. It was assumed that the current rainfall variability of 18%, determined as the coefficient of variation from the long-term rainfall data (1998–2014) using Eq. 5.1, will increase to 22% during the 2016–2030 simulation period after the baseline water year 2015. The forecast increase in rainfall variability of 22% was determined by assuming that 12 of the 15 water years will experience non-normal rainfall events including two very wet years, two wet years, three dry years, and five very dry years (Table 6.7).

Supplemental irrigation scenario

The supplemental irrigation scenario examines the potential impact of supplemental irrigation in the rainy season when refilling of the reservoir occurs on the water supply for the multiple water demands in the dry season under the current conditions of the irrigation schemes (case I) as well as under the improved system efficiency (case II). Under both scenarios, the entire irrigable area in the schemes was assumed to be cultivated with maize in the rainy season. For case II, the rainfall variability during the simulation period was taken into consideration to ascertain the limits of potential annually unmet water demands after improving the system's efficiency.

6.2.4 Evaluation of the simulation results

The simulated storage time series were analyzed using statistical indicators such as the Nash-Sutcliffe model efficiency coefficient (EF), Willmott's index of agreement (d), the coefficient of determination (R^2), and the normalized root mean square error (NRMSE) (Krause et al., 2005; Raes et al., 2012a). However, because of the unavailability of long-term historical, hydrological data on water inflow and outflow, reservoir storage, water demands and unmet demands for the multiple water users in both irrigation schemes, a calibration and validation of the WEAP model could not be carried out in this study.

6.3 Results

6.3.1 Discharge into the reservoir

The simulated range of runoff coefficients was only slightly wider in the BIS (1.3–14.1%) than in the VIS (1.4–12.4%). However, discharge varied notably in the VIS, ranging between 0.01 and 6.82 $m^3 s^{-1}$ in contrast to the narrow range (0.01 and 0.06 $m^3 s^{-1}$) in BIS. The higher discharge simulated for the Vea catchment is due to its larger catchment size compared to that of Bongo (136 km^2 vs. 0.98 km^2).

6.3.2 WEAP model performance

The results of the statistical analysis of the simulated daily storage indicate an excellent agreement (d = 1; EF = 0.99) between the observed and the simulated values with minimum errors in predictions for the BIS (Figure 6.2a). However, for the VIS, the model performed fairly (d = 0.58; EF = -2.23) with an acceptable error margin, which falls within the range of 10–20% (Raes et al., 2012a) (Figure 6.2b). The strange pattern exhibited by the observed storage in the VIS requires further investigation, as it is unclear whether it is due to the use of the designed volume-elevation curve, which probably varied from the current situation, or due to measurement irregularities.

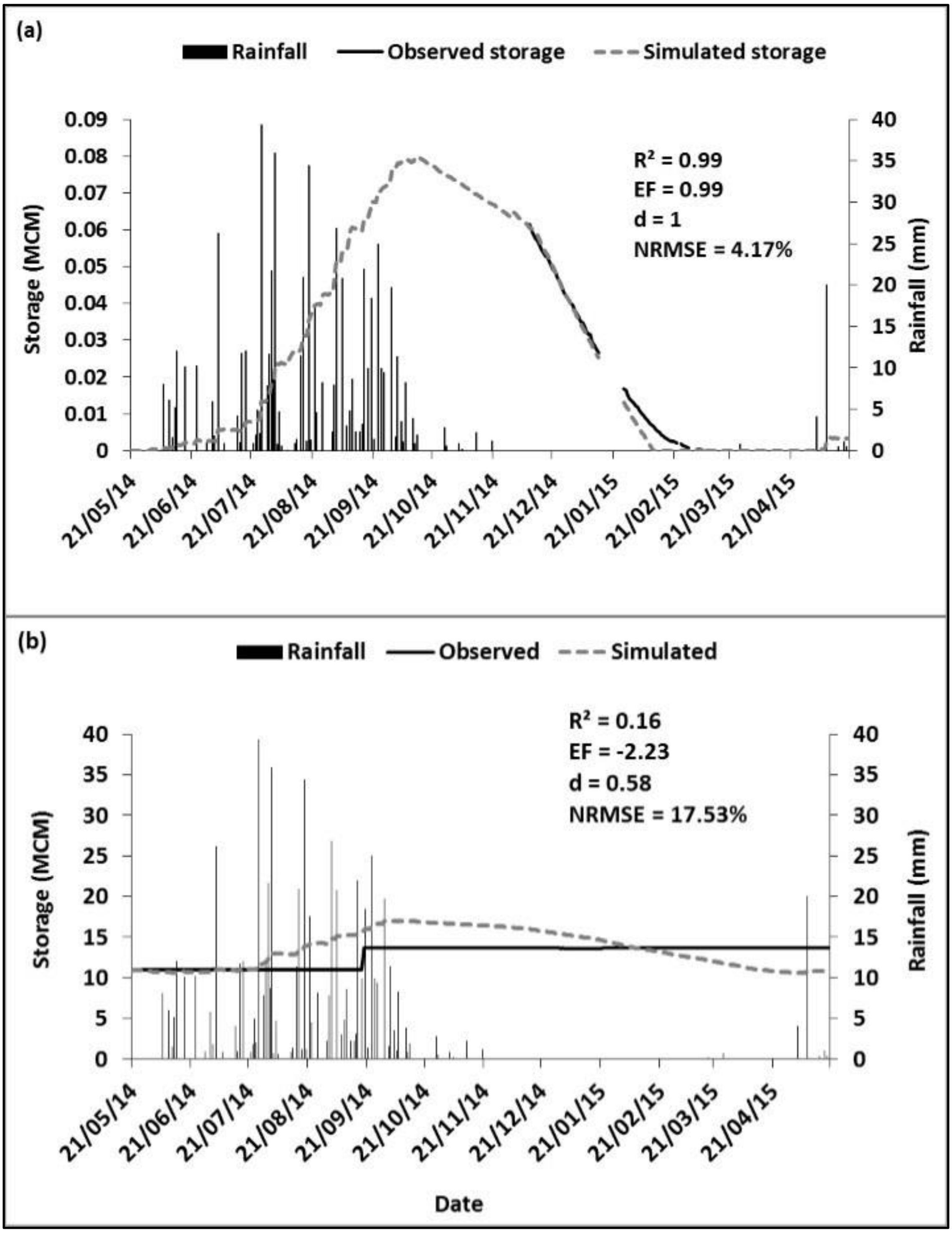

Figure 6.2 Simulated and observed daily reservoir storage during 2014–2015 in the (a) Bongo and (b) Vea irrigation schemes.

Scenario analysis

Reference scenario

The total annual water demand of the schemes and the unmet demand (water deficit) under the business-as-usual scenario increased consistently over the 2015–2030 simulation period in the BIS (Figure 6.3a, b). The total annual water demand in the VIS also showed an upward trend (Figure 6.3c), but since this demand was satisfied by the annual water supply, there were no unmet needs over the simulation period.

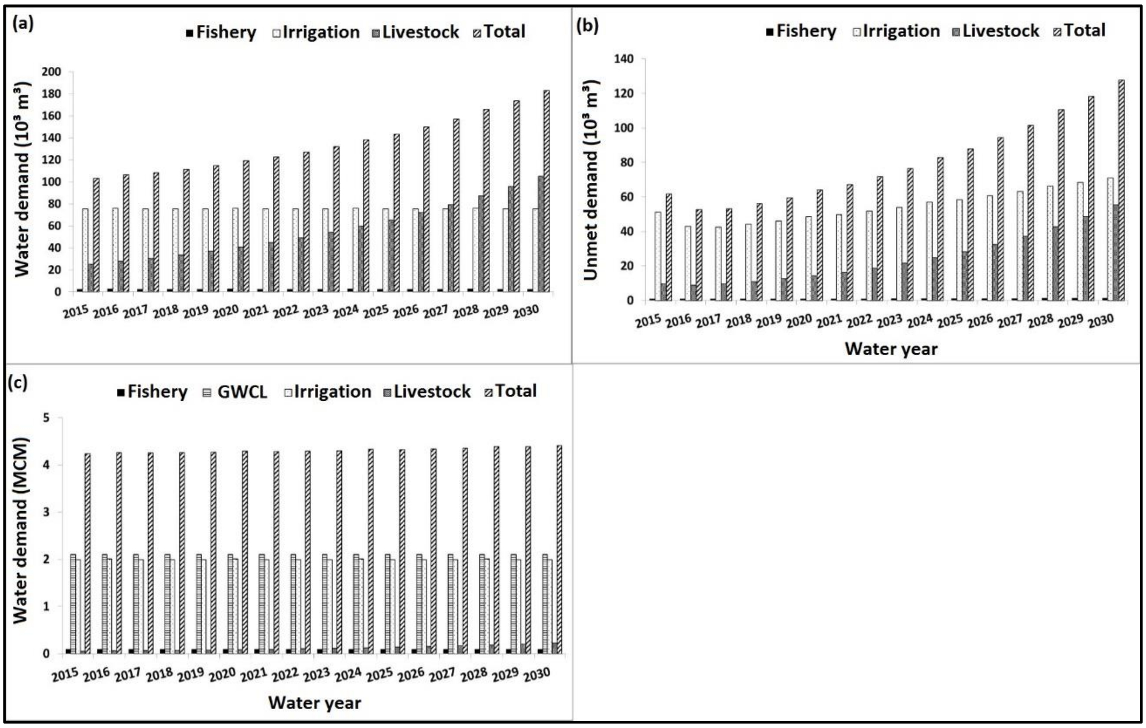

Figure 6.3 Water balance under the reference scenario: (a) water demand in Bongo, (b) unmet demand in Bongo, (c) water demand in Vea without the impact of rainfall variability during the 2015–2030 simulation period.

Rainfall variability scenario

The predicted reduction in total annual unmet water demand (AUWD) in the BIS measured 27–34% in very wet years and 3–6% in wet years. However, it increased by various degrees depending on the rainfall regime (Figure 6.4). In particular, the increase amounted to 6–11% in normal years, 13–23% in dry years, and 12–26% in very dry years.

The VIS showed no unmet demands even in very dry years, which is attributable to the storage of large quantities of water in the Vea reservoir prior to the onset of rainfall resulting from underutilization of the water resources. The water availability in the VIS was therefore not affected by the rainfall variability, as the annual supply delivered to the multiple water users matched their annual water demand.

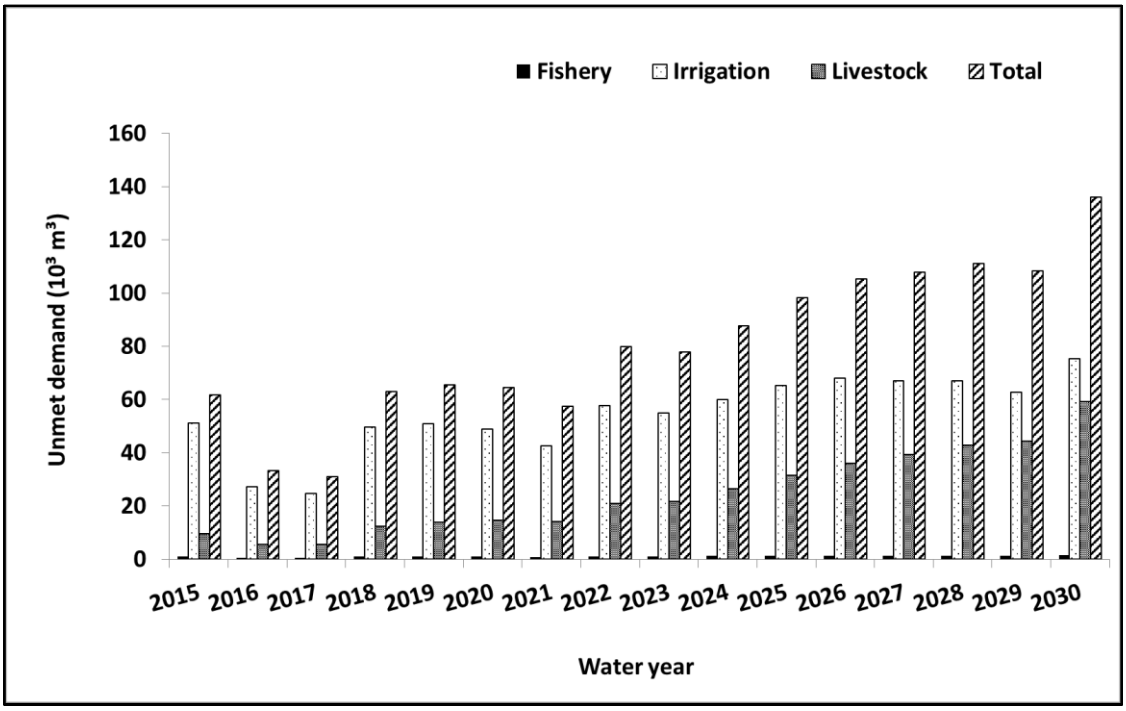

Figure 6.4 Unmet water demand in Bongo under the rainfall variability scenario.

System efficiency improvement scenario

In the BIS, the AUWD decline of 23–24% under the very wet year and of 6–13% in all other years was predicted, resulting from the increase in water availability through the improvement of the system efficiency (Figure 6.5). The steep decline in AUWD in very wet years is due to the combined effect of efficiency improvement and an increased amount of rainfall. In the VIS, the 5% reduction in annual water supply was predicted over the simulation period due to the improvement in system efficiency, thereby further increasing the water availability in the reservoir.

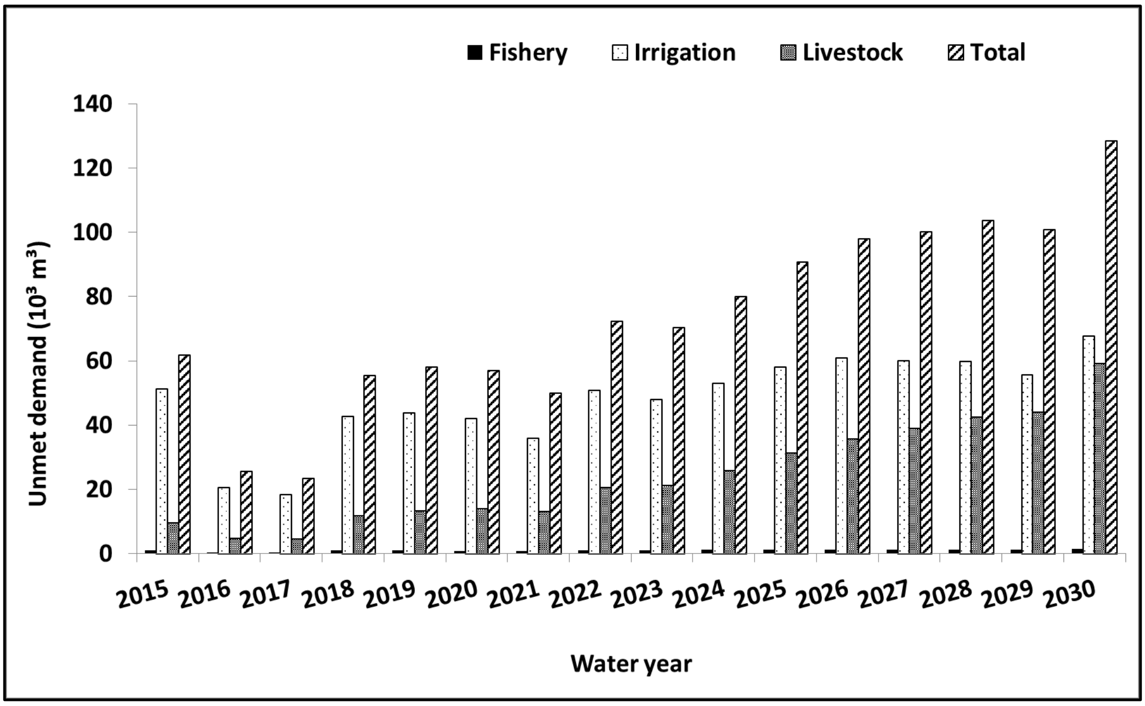

Figure 6.5 Unmet water demand in the Bongo scheme under the system efficiency improvement scenario and the impact of rainfall variability.

Supplemental irrigation scenario

The 18–80% rise in AUWD was predicted in the BIS under the supplemental irrigation scenario without the improvement in the system efficiency (Figure 6.6a). The increase measured 11–48% considering the improvement in the system efficiency (Figure 6.6b).

In the VIS, there was no unmet water demand across the multiple water users under this scenario even without considering the system efficiency improvement.

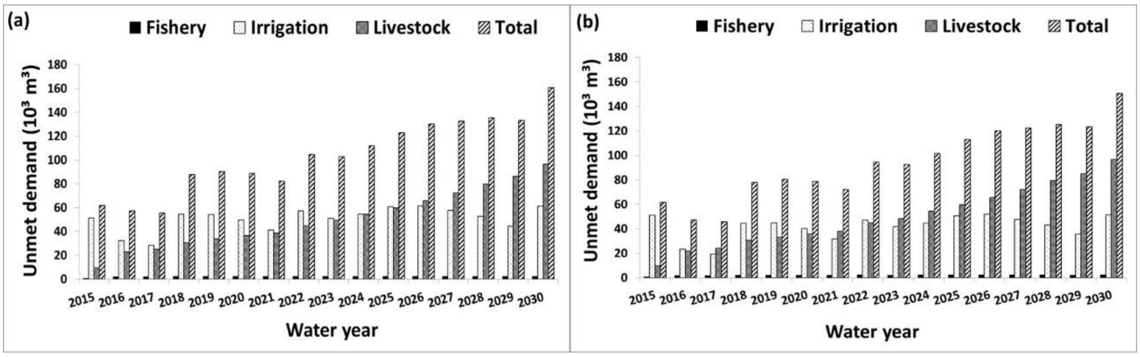

Figure 6.6 Unmet demands for multiple water users under the supplemental irrigation scenario and the impact of rainfall variability in the Bongo scheme (a) without system efficiency improvement and (b) with system efficiency improvement.

Irrigable area expansion scenario

The 8–32% increase in AUWD was revealed for all demand sites in the BIS over the simulation period resulting from the 50% expansion of the tomato cropping area and the 10% improvement in the system efficiency (Figure 6.7a). In the VIS, the supply to all the demand sites over the simulation period was enough to meet the increased water demand following the annual expansion of the cropping area coupled with the introduction of supplemental irrigation in the rainy season. Thus, no unmet demand was recorded in the Vea catchment.

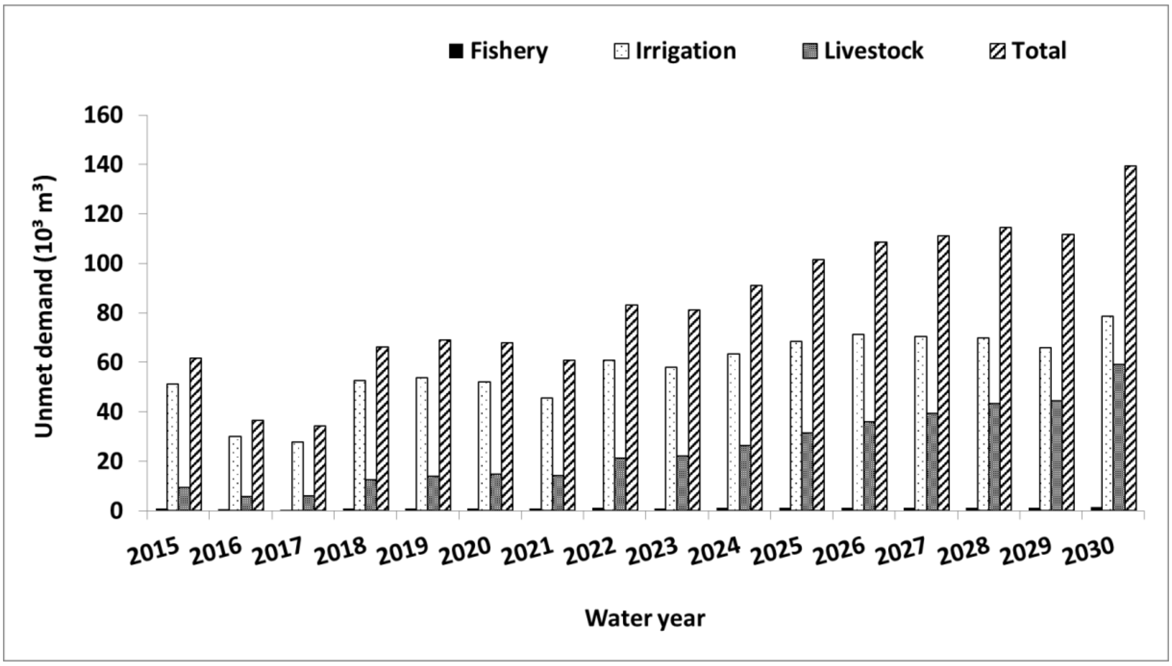

Figure 6.7 Unmet water demand in the Bongo scheme under the irrigable area expansion scenario and the impact of rainfall variability.

6.4 Discussion

6.4.1 Water availability in the reservoirs

The detected drying up of the Bongo reservoir in the later part of 2014–2015 confirms the observation by Adwubi et al. (2009) that most of the UER small reservoirs dry up toward the end of the dry season and start refilling with discharge at the beginning of the rainy season. The medium-scale Vea scheme, however, exhibited a different pattern due to the appreciable amounts of reservoir water at the onset of both rainy seasons due to the underutilization of water resources in this scheme.

The runoff coefficient, indicating the dynamics of the discharge into the Bongo and Vea reservoirs, was found to be consistent with the monthly averages of runoff coefficients ranging between 13 and 15% in the much larger Yarigatanga catchment with an area of 352 km² (Ofosu, 2011). Similarly, Sanfo et al. (2017) reported runoff coefficients of 10–25% for the Sudanian zone of West Africa.

6.4.2 Reference scenario

The annual increase in the gross water demand in both irrigation schemes under current practices and condition of the schemes was due to the increasing water demand of livestock resulting from the annual livestock population growth rate of 10%. As a consequence of the low reservoir storage in 2014–2015 in Bongo, the water supply was insufficient to meet the gross demands. Although the unmet demand declined in 2015–2016, resulting from an increased water supply, it grew further over the simulation period due to the rising water demand for livestock.

In Vea, where the reservoir storage by far exceeded the total scheme's water demand, the livestock population growth had no effect on the water balance.

6.4.3 Rainfall variability scenario

The impact analysis of rainfall variability on reservoir storage indicates that this factor significantly influenced the sufficiency of water supply for the multiple users. The size of the water storage infrastructure (dam) was a less influential factor in that respect in the BIS in particular, where the reservoir was not filled up to the capacity in 2014–2015 resulting in water shortages. Fowe et al. (2015) also stated that rainfall variability influenced reservoir storage in the Volta basin based on the dependency of runoff generation in the upstream catchments on the rainfall pattern.

The water sufficiency in the Vea scheme during the very dry year with an extremely low discharge was due to the relatively large upstream catchment feeding the Vea reservoir coupled with the full storage of the reservoir at the beginning of the rainy season.

6.4.4 System efficiency improvement scenario

The simulated improvement in the system efficiency suggests that it is an important strategy for water saving and subsequently increasing the water availability for the competing water users in the Bongo scheme. As stated earlier (Chapter 3), system efficiency improvement could be achieved primarily through canal system rehabilitation to reduce seepage and percolation losses as well as appropriate and efficient water application at field level. Mutiga et al. (2010) also stated (standard error 0.18%) that an improved reservoir-based irrigation system efficiency would reduce unmet water demands by enhancing water availability in the upper Ewaso Ng'iro north basin in Kenya. As a long-term strategy to improve and sustain a high system efficiency, the shift from furrow irrigation practiced at present towards sprinkler and simplified drip systems could be considered.

6.4.5 Irrigable area expansion scenario

The simulation results indicate that increasing the cropping area for tomato production in the small-scale BIS, which depends solely on the reservoir water supply, would not be an adequate option at present. On the one hand, the expansion of the tomato cropping area is likely to increase the unmet water demands among the multiple water users. On the other hand, cropland cultivated with tomato, a water-intensive crop, would be at more risk of water shortages and yield failure.

6.4.6 Supplemental irrigation scenario

The investigation of the schemes' water balances suggests that supplemental irrigation in the rainy season would not conflict with the maintenance of the reservoir storage for the dry season water needs. This is because the annual supply delivered under the supplemental irrigation scenario without improving system efficiency (case I), and the quantity delivered after the efficiency improvement and considering the impact rainfall variability (case II) were the same within each scheme over the 2015–2030 simulation period. However, the simulated increase in the annual unmet water demand across the multiple water users in the BIS indicates that supplemental irrigation has to be introduced with caution. The latter implies consultations with relevant stakeholders including the WUA, agricultural extension agents and chiefs coupled with education on the potential impacts.

In contrast, the VIS simulations suggest no restrictions for the introduction of supplemental irrigation using the current infrastructure in this medium-scale scheme.

6.4.7 Research limitations and outlook

As water is becoming increasingly scarcer owing to climate variability and increased competing demands, exploiting groundwater from shallow wells to supplement water supply during periods of low reservoir storage is a scenario to explore in further analyses. The monitoring of the groundwater dynamics in the study area revealed a shallow groundwater table ranging from 0.6–1.3 m and 0.7–2.8 m on average in the Bongo and Vea irrigation schemes, respectively (Figure 4.4). The exploitation of groundwater resources in conjunction with system efficiency improvement was suggested as a potential option to enhance water security in West Africa (e.g., Höllermann et al., 2010). Such an intervention is, however, currently hindered by the lack of adequate information about the potential of groundwater resources for irrigation coupled with land tenure issues, lack of access to efficient drilling technology, and financial constraints (Namara et al., 2011). Raising the system efficiency may have the potential to limit groundwater use, as percolation recharging the groundwater would be reduced. Hence, conjunctive use options require careful analysis and should be a part of long-term water management planning in reservoir-based irrigation schemes.

Further analysis should take into account the surface and groundwater quality, as poor water quality could render large quantities of available water unusable for livestock, fishery and domestic use, in some cases (e.g. heavy metal pollution in several gold mining areas in Ghana including the UER) unusable even for irrigation (Cobbina et al., 2015; Kpan et al., 2014). However, the assessment focusing on water quantity in this research is a prerequisite for future studies focusing on developing adaptation strategies for multiple water users in reservoir-based irrigation schemes in the UER.

6.5 Conclusions

The model-based scenario analysis explored relevant adaptive options in the reservoir-based irrigation schemes in the UER to face future needs of increasing crop production and productivity while reconciling the water demand of other sectors and coping with increasing variability in rainfall. The 6–26% increase in the water supply-demand gap was predicted due the rainfall variability in both study schemes. In the small-scale scheme of Bongo, the introduction of supplemental irrigation in the rainy season could be possible only if the rise in demand is counterbalanced by about 10% increase in system efficiency and by setting limits on the cultivation of the water-intensive tomato crop in the dry season. In the medium-scale scheme of Vea, the available water is underutilized due to the deteriorated water delivery infrastructure. With canal system rehabilitation, VIS would have the capacity to meet the gross water demand should the whole potentially irrigable area be put under crop cultivation in both rainy and dry seasons with the afore-mentioned principal crops. Water allocation for fisheries is compromised in periods of water shortages in the small-scale Bongo scheme, as livestock consumes the reservoir's dead storage.

The WEAP model proved to be a user-friendly and adaptable-to-local context tool for the simulation of future water supply-demand nexus in multi-purpose, reservoir-based irrigation schemes of the UER, but the simulation results remain to be validated against field observations. Further scenario-based analysis should be applied to assess the contribution of groundwater resources to reducing water shortages in reservoir-based schemes, the impact of rising temperature as well as evaporation on water availability in those schemes.

7 OVERALL DISCUSSION AND CONCLUSIONS

7.1 Integrated management of water resources in multi-purpose reservoir-based irrigation schemes under climate variability

The increasing demand for year-round water availability in smallholder farming systems in arid and semi-arid regions of SSA for food security necessitates the development and implementation of appropriate, efficient and sustainable water management strategies. This study applied an integrated approach for whole-system assessment of the performance of typical, small- and medium scale reservoir-based irrigation schemes to reveal the current performance levels and priority areas within the system for irrigation performance improvement. This helped to gain a holistic view of scheme performance including the aspects of reservoir, water conveyance and distribution network, cropping field, management entity and multiple users as well as the interaction between multiple water users besides irrigators.

The results indicate that the water resources of the medium-scale VIS are underutilized, as less than 40% of the total storage was in use. This implies a huge potential for an improvement primarily through the rehabilitation of the deteriorated water delivery infrastructure, the main cause of the underutilized potenial. In particular, the overall system efficiency in the small- and medium-scale irrigation schemes can be increased from 50% to 68% by reducing losses in the currently malfunctioning water conveyance network. This technical intervention would require significant costs that might not be afforded in the nearest future. Another, cost-effective option that can be immediately pursued for increasing the system's efficiency is through improving the field-scale irrigation scheduling. Over-irrigation observed at field level in both the small- and medium-scale irrigation systems led to water wasting and adverse impacts on crop-water productivity. Under improved irrigation schedules, a relatively high application efficiency at field level (58–68%) is achievable under the conditions of small- and medium-scale schemes in the UER. The findings of this evaluation fill the knowledge gap in the performance of reservoirs in the UER of Ghana and also in general for SSA in the context of water scarcity by providing quantitative information about the current performance levels of the Vea and Bongo irrigation schemes. The huge potential in both schemes yet to be unlocked for improved water management leading to increased agricultural productivity and livelihood improvement is revealed. Furthermore, the results serve as a starting point for improvements by tackling the reasons for the current performance deficits. Given the applied nature of this study, it provides policy makers and irrigation scheme managers with up-to-date information for planning water-related interventions in the agricultural sector by drawing on the information about the current performance levels and the existing potentials in the reservoir-based irrigation schemes in the region.

Under increasing climate variability and population growth in SSA (Asfaw et al., 2018; Boko et al., 2007; Sylla et al., 2016), any interventions for improving the water use efficiency and water productivity need to be adapted to the changing environment. This study explored suitable intervention scenarios considering the multi-purpose use of water reservoirs and observed climate variability over the 2015–2030 period through simulation analysis using the WEAP model. Rainfall variability will likely increase the water supply–demand gap by 6–26% depending on the rainfall regime, causing severe water shortages in the small-scale scheme. The simulation results confirm the necessity of improving irrigation system efficiency to reduce total unmet demand by increasing water availability for the livestock and fishery sectors competing with crop irrigation. The medium-scale scheme currently has the capacity to meet the gross water demand of the multiple water users even in the scenario where all the potentially irrigable area of the scheme is put under year-round tomato-maize crop cultivation. The study brings to light the importance of integrating the user-specific water demands of competing water users in multi-purpose reservoirs for equitable water allocations by employing modeling tools in defining the water use(s) to be prioritized in times of shortages. The implementation of the integrated approach to reservoir operation highlighted in this study could forestall potential water-related conflicts.

7.2 Year-round irrigation management as a feasible adaptation strategy under water scarcity

The whole-system assessment has revealed that improved irrigation schedule to reduce water wastage or inadequate water supply at field level is crucial for improving water management and increasing crop water productivity in small- and medium-scale irrigation schemes, particularly under the observed temporal variability in rainfall (Sekyi-Annan et al., 2018a). The field-level assessment using AquaCrop model focused on both irrigation schedules to ensure a reduction of the associated risks in rainfed crop production as well as an appropriate water use during the dry season. The intra-seasonal variability of rainfall revealed by the frequency of dry spells was found to have a greater influence on water demand for crop growth and yield than the total rainfall over the growing season in contrast to the conclusion by Guan et al. (2015) that intra-seasonal rainfall variability is less relevant for crop yield than total rainfall. The estimated magnitude of water saving under the improved irrigation schedule (130–1,325 mm) amounted to 22–52% of the GIA under the current irrigation practices. Considering only the crop irrigation sector, the quantity of water saved through improved irrigation scheduling of dry-season tomato is largely sufficient to accommodate supplemental irrigation of maize in the rainy season, and thus adapted to the rainfall variability and recurrent dry spells. Even for the dry climate scenario of low rainfall coupled with frequent dry spells, about 126 mm of water at field level would be required for the supplemental irrigation of maize during the rainy season. However, because of the heterogeneity within and between cropping fields, there is a need to account for the spatial variability in hydrogeological features of these fields in irrigation scheduling. The simulated increase in maize yield upon the introduction of supplemental irrigation offers an incentive for managers of the Bongo and Vea schemes to explore this strategy.

In the context of multiple water users in the scheme, the option of supplemental irrigation in the rainy season currently appears feasible only in the medium-scale scheme. In the small-scale scheme, supplemental irrigation could be possible only if the rise in water demand is counterbalanced by about 10% increase in system efficiency and by setting limits on the cultivation of the water-intensive tomato crop in the dry season. Moreover, due to the reservoir losses through evaporation and seepage, some of the water saved in the dry season might not be available for the supplemental irrigation in the rainy season. Hence, the whole system water balance by juxtaposing the total available reservoir water with the gross user-specific water demands for all competing water users all year round, and an effective year-round irrigation schedule is required to ensure that supplemental irrigation in the rainy season does not compromise water availability for the dry-season crop production. The possibility of introducing supplemental irrigation in the rainy season as an adaptation strategy in reservoir-based irrigation schemes, and the necessary pragmatic steps to be undertaken for its realization have been highlighted in this study.

In January 2017, the Government of Ghana, through the Ministry of Food and Agriculture, expressed the intention to revamp the agricultural sector by implementing strategies to ensure a year-round farming in order to achieve food sufficiency and agro-economic development. Hence, the knowledge revealed in this study about the improved irrigation schedule for tomato, and the supplemental irrigation requirement for maize in Vea and Bongo could be a useful resource for the implementing agencies and institutions. The adoption of the improved irrigation schedule and supplementary irrigation by farmers would require significant involvement of agricultural extension services.

7.3 Advantages and limitations of using modeling tools in agricultural water management

The application of modeling tools in this study has facilitated the formulation of suitable water-use options under climate variability in the reservoir-based schemes studied both at field scale (AquaCrop) and scheme scale (WEAP). In particular, the AquaCrop model is a reliable tool for developing year-round irrigation schedules for cropping systems in reservoir-based irrigation schemes. AquaCrop enhanced the evaluation of the appropriateness and in turn efficiency and effectiveness of the traditional irrigation practices, creation of a site-specific irrigation schedule for tomato, and estimation of the supplemental irrigation requirement for rainfed maize at field level.

The limitation of the AGB time series to only four samples during the crop cycle and once at harvest due to farmer ownership and management of fields affected the ability of AquaCrop to interpret completely the variations between the simulated and observed data, as EF varied widely from 0.23–0.83, and NRMSE ranged from 11.5–42% across crops. Hence, monitoring data on researcher-managed experimental fields might be appropriate. Furthermore, the inability of AquaCrop to simulate nutrient dynamics and their impact on crop yield mostly likely reduced the magnitude of the simulated potential yield increase under the improved irrigation schedule. Hence, a combination with a crop growth model such as DSSAT (Jones et al., 2003) would be needed for assessing the impact of improved irrigation scheduling on crop growth and yield.

At scheme level, the WEAP model was useful for the simulation of the future evolution of the water supply-demand nexus in the small- and medium-scale reservoir-based irrigation schemes in the UER. Using the daily time step enabled the model to display the interaction between the multiple water demands with appropriate frequency. Because of the potential dire impacts of water shortage in dry regions, knowledge of the real-time impacts is useful in devising preventive measures.

The unavailability of long-term historical data was a major drawback of the scenario-based analysis, as this challenge prevented the calibration and validation of the WEAP model. However, the use of recommended methods (Sieber and Purkey, 2015) enabled the assessment of the potential adaptation options to water scarcity. Nonetheless, the lack of WEAP calibration and validation compromised the model's ability to mimic completely the actual situation in the reservoir-based irrigation schemes, which thus calls for caution in the application of the simulation results where EF and NRMSE are 0.99 and 4.17% in the small-scale scheme, respectively, and -2.23 and 17.53% in the medium-scale scheme, respectively. Continuous whole-system data collection on inflows and outflows in reservoir-based irrigation schemes will facilitate future performance assessments.

Furthermore, the exclusion of a water quality assessment for both the reservoir and groundwater is another limitation of this study, as a poor water quality could render large quantities of available water unusable. However, the assessment focusing on water quantity in this research is a prerequisite for future studies focusing on developing adaptation strategies for multiple water users in reservoir-based irrigation schemes in the UER.

The methods employed in data collection for the calculation of the performance indicators in this study provided valuable quantitative information about the reservoir-based irrigation schemes as a whole. However, according to Bos et al. (2005), the errors associated with these measurements range between 1% in the determination of irrigation interval, and 25% in the extrapolation of point data on soil moisture to field scale. Nonetheless, the whole-system approach implemented in this study coupled with the scenario-based assessment of performance is an appropriate step towards equitable and sustainable reservoir operations in water-scarce regions.

7.4 Outlook and future research needs

In spite of the challenges plaguing the smallholder irrigation schemes in the UER, a huge potential exists in the schemes to support rural agro-economic development for the achievement of the SDGs of attaining food security, promoting sustainable agriculture, and ensuring the availability and sustainability of water resources. Given the forecast impact of climate change and variability on water availability in the UER, and in arid and semi-arid SSA at large, diversifying water resources in smallholder agricultural systems should be explored. In particular, supplemental irrigation from reservoirs in the rainy season should be taken into consideration. Future studies quantifying the groundwater resources for crop production and the intra- and inter-seasonal variability of the groundwater table would be worthwhile in this respect. Further research also need to focus on a detailed assessment of all contributing factors in crop-water productivity, especially the interaction between soil moisture and nutrient dynamics, as soil nutrient is another influential factor in crop productivity in the savanna due to the inherently poor soils. The interplay between soil moisture and rising temperature (heat stress) is another relevant research topic. Overall, a catchment-scale assessment, capturing the spatial variability of the multiple uses of inland valleys in SSA appear most appropriate in optimizing the use of natural resources in these valleys.

Besides these research needs, there are also priorities for local development. In particular, there is the need to upgrade the schemes through the installation of flow measuring devices to enable the measurement and proper dosage of irrigation water delivery and application, and to enhance the up-to-date performance evaluation of the schemes for efficient water management. Furthermore, the training of water users on the subject of climate change and the need to adopt best irrigation practices, and their inclusion in decision making about reservoir operations could enhance the improvement of the reservoir-based schemes under variable environmental conditions.

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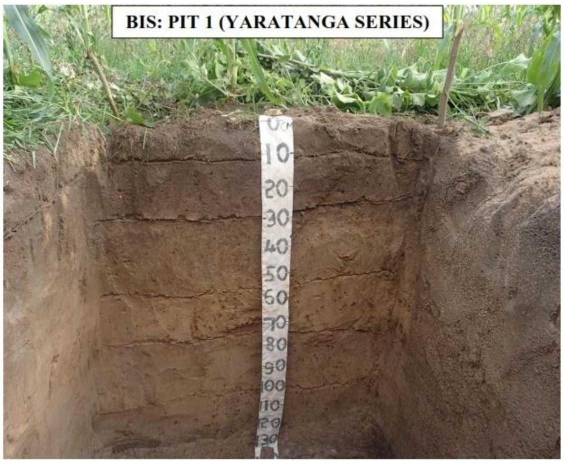
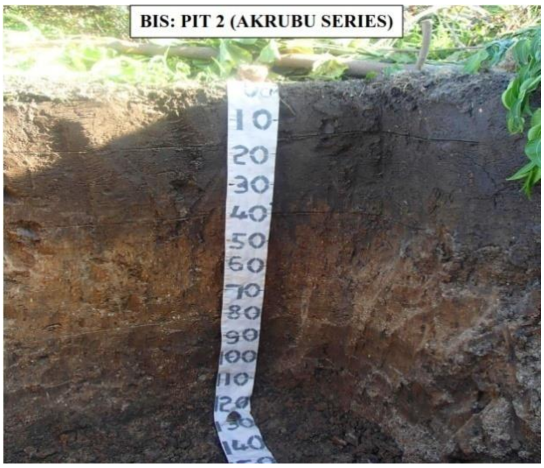
9 APPENDICES

Appendix 9.1 Pictures of the soil profiles in the Bongo irrigation scheme (BIS) and Vea irrigation schemes (VIS)





Appendix 9.2 Soil profile description in the Bongo irrigation scheme

Pit 1 (10° 54’ 46.0’’ N, 00° 47’ 30.8’’ W) - Yaratanga series		
Horizon	Depth (cm)	Description
Ap	0–12	Dark brown (10YR 3/3) moist; sandy loam; weak fine granular; loose, non-sticky non-plastic; porous, many very fine and fine roots; rusty root channels; clear smooth boundary.
ABg	12–30	Dark yellowish brown (10YR ¾) moist; common fine faint brown mottled; loamy sand; very few fine quartz gravels; weak fine granular; very friable; high pores, common to few fine roots, clear smooth boundary.
Bg	30–56	Light olive brown (2.5Y6/6) moist; common fine distinct brownish yellow mottled; sandy loam; weak fine subangular blocky; friable; very few fine roots; clear smooth boundary.
BCg	56–75	Olive yellow (2.5Y 6/6) moist; common fine faint olive yellow (2.5Y 5/6) mottled; sandy loam; weak fine granular, friable, slightly sticky slightly plastic; clear smooth boundary.
CBg	75–100	Light olive brown (2.5Y 6/4) moist; sandy loam; common fine distinct light brownish gray mottled; sandy loam; single grain; loose; gradual smooth boundary.
Cg	100–125	Light olive brown (2.5Y 6/4) moist; loamy sand; many fine and medium distinct yellowish red mottles; structureless; loose;
	125+	Water table encountered

Appendix 9.3 Soil profile description of Bongo irrigation scheme (continued)

Pit 2 (10° 50’ 47.1’’ N, 00° 52’ 28.0’’ W) - Akrubu series		
Horizon	Depth (cm)	Description
Ap	0–20	Black (10YR 2/1) moist; silty loam; rusty root channels weak fine crumbs; very friable; few fine roots, gradual smooth boundary.
ABgk	20–44	Very dark brown (10 YR 2/2) moist; rusty root channels; common fine faint olive yellow mottles; loam; few fine quartz gravels; moderate medium subangular blocky to massive; slightly sticky slightly plastic, few fine roots, moderately calcareous, few manganese dioxide concretion(3% by vol); clear smooth boundary
Bgkcs1	44–80	Light olive brown (2.5Y6/8) moist; loam; mottled olive yellow; massive; slightly sticky slightly plastic; common fine quartz gravels; few iron and manganese dioxide nodules; strongly calcareous; gradual smooth boundary
Bgkcs2	80–120	Olive brown (2.5Y 4/3) moist; mottled light olive brown; clay; massive, sticky plastic; few fine quartz gravels; common manganese dioxide and iron concretion; strongly calcareous

Appendix 9.4 Soil profile description in the Vea irrigation scheme

Pit 3 (10° 50’ 46.9’’ N, 00° 52’ 28.2’’ W) - Akrubu series		
Horizon	Depth (cm)	Description
Ap	0–20	Dark brown (10YR3/3) moist; rusty root channels; sandy loam; weak fine granular and crumbs with worm cast , very friable, many very fine and fine roots; clear smooth boundary
ABg	20-32	Dark yellowish brown (10YR4/4)moist; common fine distinct yellowish red mottles; sandy clay loam; moderate medium and coarse subangular blocky to porous massive; slightly hard to hard, firm to very firm, sticky plastic; thick clay and humus cutans; few manganese concretion, very few fine roots; gradual smooth boundary.
Bcsgk	32–57	Light olive brown (2.5Y 5/4)moist; few fine faint olive yellow mottles; gritty clay; common fine quartz gravels and manganese dioxide concretions, massive; sticky plastic; very few very fine roots, moderately calcareous; gradual smooth boundary
CBcsgk	57–76	Olive yellow (2.5Y 6/6) moist; common fine distinct grayish brown mottles; gritty clay; few fine quartz gravels (2%); massive; sticky plastic; strongly calcareous; common manganese dioxide and calcium carbonate nodules; diffuse smooth boundary.
Ccsgk	76–120/128	Olive yellow (2.5Y 6/6) moist; common fine distinct gray mottles; gritty clay; common fine quartz gravels (6%); massive; sticky plastic; strongly calcareous; common manganese dioxide and calcium carbonate nodules

Appendix 9.5 Chemical properties of soils in the Bongo and Vea irrigation schemes

					Exchangeable cations (cmol/kg)								Available-Brays	
Profile depth (cm)	pH (1:1 H_2O)	OC (%)	Total N (%)	OM (%)	Ca	Mg	K	Na	TEB (cmol kg^{-1})	EA (cmol kg^{-1})	CEC (cmol kg^{-1})	BS (%)	ppmP	ppmK
Pit 1														
0-12	6.5	1.44	0.16	2.48	3.20	0.80	0.08	0.04	4.12	0.15	4.27	96.49	26.95	31.19
12-30	7.0	0.41	0.06	0.71	4.01	1.07	0.04	0.03	5.15	0.15	5.30	97.17	5.50	13.25
30-56	7.2	0.34	0.04	0.59	2.94	1.07	0.03	0.03	4.07	0.05	4.12	98.79	2.55	10.56
56-75	7.1	0.21	0.04	0.36	1.34	1.07	0.02	0.02	2.45	0.50	2.95	83.05	1.99	8.23
75-100	7.9	0.14	0.03	0.24	2.40	1.07	0.04	0.30	3.81	0.03	3.84	99.22	3.11	11.03
100-125	7.9	0.07	0.02	0.12	2.14	1.60	0.03	0.03	3.80	0.03	3.83	99.22	0.88	12.98
Pit 2														
0-20	7.8	1.75	0.16	3.02	15.49	7.34	0.09	0.06	22.98	0.05	23.03	99.78	34.12	35.14
20-44	8.4	0.51	0.07	0.88	9.08	5.07	0.10	0.06	14.31	0.03	14.34	99.79	2.79	37.12
44-80	8.7	0.34	0.04	0.59	7.08	4.01	0.10	0.06	11.25	0.03	11.28	99.73	0.24	38.62
80-120	8.8	0.31	0.04	0.53	8.28	11.21	0.10	0.06	19.65	0.03	19.68	99.85	1.59	34.21
Pit 3														
0-20	7.3	0.72	0.09	1.24	3.74	1.87	0.15	0.08	5.84	0.05	5.89	99.15	13.87	52.48
20-32	7.7	0.48	0.07	0.83	4.81	3.07	0.07	0.04	7.99	0.05	8.04	99.38	28.70	24.31
32-57	8.5	0.45	0.07	0.78	8.01	6.14	0.08	0.04	14.27	0.05	14.32	99.65	0.40	29.67
57-76	8.2	0.41	0.06	0.71	10.68	8.41	0.10	0.06	19.25	0.03	19.28	99.84	0.48	35.29
76-120/128	8.2	0.31	0.05	0.53	18.16	11.35	0.19	0.08	29.78	0.05	29.83	99.83	0.48	70.13

OC = Organic carbon, OM = Organic matter, TEB = Total exchangeable bases, EA = Exchangeable acidity, CEC = Cation exchange capacity, BS = Base saturation

Appendix 9.6 Physical and hydraulic properties of soils in the Bongo and Vea irrigation scheme

Depth (cm)	Soil texture	Bulk density (g cm $^{-3}$)	SAT (%)	FC (%)	PWP (%)	TAW (%)	K_{sat} (mm day^{-1})
Pit 1 (Bongo irrigation scheme)							
0-12	Sandy loam	1.10	49.7	16.9	6.2	10.6	1,744
12-30	Loamy sand	1.27	47.5	19.1	4.3	14.9	1,816
30-56	Sandy loam	1.26	45.8	19.1	5.8	13.3	1,318
56-75	Sandy loam	1.28	46.7	14.1	4.2	9.9	1,641
75-100	Sandy loam	1.36	45.2	18.3	6.4	11.9	1,109
100-125	Sandy loam	1.44	44.2	17.8	6.3	11.6	885
Pit 2 (Bongo irrigation scheme)							
0-20	Silt loam	1.07	51.5	34.2	11.0	23.2	632
20-44	Loam	1.32	44.6	31.1	12.6	18.5	363
44-80	Loam	1.53	45.1	40.7	18.7	22.0	261
80-120	Loam	1.40	45.7	44.2	14.8	29.4	192
Pit 3 (Vea irrigation scheme)							
0-20	Sandy loam	1.37	47.3	20.3	5.4	14.9	1,473
20-32	Sandy loam	1.59	45.3	22.0	8.8	13.2	625
32-57	Loam	1.57	45.1	32.9	14.8	18.1	226
57-76	Loam	1.56	47.0	38.6	14.0	24.6	159
76-128	Clay loam	1.52	49.7	47.3	17.5	29.8	86

SAT = Saturated water content, FC = Field capacity, PWP = Permanent wilting point, TAW = Total available water, K_{sat} = Saturated hydraulic conductivity determined from pedo-transfer functions

Appendix 9.7 Infiltration capacity of soils in the Bongo and Vea irrigation schemes

Test location	Soil type	Initial f_o (mm h^{-1})	f_p after 3 h (mm h^{-1})	Mean f_p (mm h^{-1})	Standard error (mm h^{-1})
Bongo irrigation scheme					
BF1 A	Gleyic arenosol	180	78	76	11
BF1 B	Gleyic arenosol	60	204	296	32
BF4 A	Calcic gleysol	60	42	21	4
BF4 B	Calcic gleysol	60	42	71	9
Vea irrigation scheme					
BNF2 A	Calcic gleysol	180	54	85	20
BNF2 B	Calcic gleysol	1260	24	367	45

f_o = Initial infiltration capacity, f_p = infiltration capacity, 3 h = Duration of measurement

Appendix 9.8 Estimated population of different livestock species that depend on the Bongo and Vea reservoirs

Livestock species	Population		
	2014	2015	2016
Bongo irrigation scheme			
Cattle	2,384	2,623	2,885
Donkeys	714	785	863
Sheep	3,664	4,030	4,433
Goats	4,286	4,714	5,186
Vea irrigation scheme			
Cattle	5,780	6,358	6,993
Donkeys	87	96	105
Sheep	6,394	7,033	7,736
Goats	8,758	9,634	10,598

Appendix 9.9 Fishery water requirement in the Vea irrigation scheme

Pond label	Surface area (ha)	Storage (m^3)
Pond 1_Lateral 1	0.19	2,850
Pond 2_Lateral 1	0.36	5,400
Pond 3_Lateral 1	0.36	5,400
Pond 5_Lateral 1	0.36	5,400
Pond 6_Lateral 1	0.36	5,400
Pond 7 A_Lateral 1	0.23	3,450
Pond 7 B_Lateral 1	0.23	3,450
Pond 8_Lateral 1	0.5	7,500
Pond 9_Lateral 1	0.5	7,500
Pond 10 A_Lateral 1	0.23	3,450
Pond 10 B_Lateral 1	0.23	3,450
Pond 1_Lateral 2	0.06	900
Pond 2_Lateral 2	0.06	900
Pond 3_Lateral 2	0.06	900
Pond 5_Lateral 2	0.5	7,500
Pond 6_Lateral 2	0.5	7,500
Pond 7_Lateral 2	0.5	7,500
Pond 8_Lateral 2	0.5	7,500
Pond 9_Lateral 2	0.36	5,400
Pond 10_Lateral 2	0.09	1,350
Pond 11_Lateral 2	0.09	1,350
Pond 12_Lateral 2	0.09	1,350
Total		**95,400**

Average depth = 1.5 m

Appendix 9.10 Volume of water abstracted from the Vea reservoir by the Ghana Water Company limited (GWCL), Bolgatanga

Month	Volume of water abstracted (m^3)			
	2013	2014	2015	2016
January	178,823	168,779	169,846	183,359
February	152,907	165,819	164,377	175,706
March	237,138	190,272	185,414	183,847
April	179,285	178,572	165,834	171,062
May	176,842	180,714	182,834	181,236
June	173,389	166,914	172,724	n.d.
July	176,253	181,622	173,516	n.d.
August	176,131	186,633	158,798	n.d.
September	151,114	164,052	155,042	n.d.
October	169,020	182,659	168,617	n.d.
November	179,887	172,981	162,832	n.d.
December	178,970	181,985	186,128	n.d.
Total	**2,129,759**	**2,121,002**	**2,045,962**	

n.d. = not determined

Appendix 9.11 Observed farming practices in the Vea and Bongo irrigation schemes in the 2014 rainy season. DAP: Days after planting

Field label	Crop	Plot size (ha)	Planting method	Planting date	Harvesting date	Growing period (DAP)
Bongo irrigation scheme						
BF1	Maize	0.14	Dibbling	May 24, 2014	September 14, 2014	113
BF2	Sorghum (S)/Millet (M)	0.02	Dibbling	May 24, 2014	M: August 23, 2014 S: October 14, 2014	91 143
BF3	Sorghum (S)/Millet (M)	0.01	Dibbling	May 24, 2014	M: August 28, 2014 S: October 14, 2014	96 143
BF4	Rice	0.10	Dibbling	July 9, 2014	October 24, 2014	107
Vea irrigation scheme						
VF1	Maize	0.07	Dibbling	July 3, 2014	September 25, 2014	84
VF2	Rice	0.03	Transplanting	June 26, 2014	October 11, 2014	107
BNF1	Maize	0.30	Dibbling	June 22, 2014	September 18, 2014	88
BNF2	Sorghum (S)/Millet (M)	0.30	Dibbling	May 31, 2014	M: August 14, 2014 S: October 20, 2014	75 142
BoNF2	Rice	0.05	Transplanting	August 4, 2014	October 30, 2014	87

Appendix 9.12 Observed farming practices in the Vea and Bongo irrigation schemes in the 2014–2015 dry season. DAP: Days after planting

Field label	Crop	Plot size (ha)	Planting method	Planting date	Harvesting date	Growing period (DAP)
Bongo irrigation scheme						
BF1	Tomato	0.04	Transplanting	October 21, 2014	February 11, 2015	113
BF2	Roselle	0.03	Dibbling	November 26, 2014	December, 26, 2014	30
BF2*	Cowpea	0.02	Dibbling	December 26, 2014	January 21, 2015	26
BF2*	Roselle	0.02	Dibbling	January 02, 2015	February 11, 2015	40
BF3	Lettuce	0.02	Transplanting	December 04, 2014	January 21, 2015	48
BF5	Rice	0.04	Transplanting	November, 07, 2014	n.d.	n.d.
BF6	Tomato	0.10	Transplanting	November 11, 2014	March 06, 2015	115
Vea irrigation scheme						
VF1	Tomato	0.07	Transplanting	December 14, 2014	n.d.	n.d.
VF2	Rice	0.05	Transplanting	February 26, 2015	n.d.	n.d.
BNF1	Tomato	0.05	Transplanting	February 12, 2015	n.d.	n.d.
BNF2	Roselle	0.04	Dibbling	February 12, 2015	n.d.	n.d.
BoNF2	Rice	0.06	Transplanting	February 12, 2015	n.d.	n.d.

** = Second cultivation, n.d. = not determined*

Appendix 9.13 Observed farming practices in the Vea and Bongo irrigation schemes in the 2015–2016 dry season. DAP: Days after planting

Field label	Crop	Plot size (ha)	Planting method	Planting date	Harvesting date	Growing period (DAP)
Bongo irrigation scheme						
BF1	Tomato	0.04	Transplanting	November 23, 2015	n.d.	n.d.
BF2	Cowpea	0.03	Dibbling	December 3, 2015	January 22, 2016	50
BF2*	Cowpea	0.03	Dibbling	January 24, 2016	March 4, 2016	40
BF2**	Roselle	0.03	Dibbling	March 4, 2016	April 4, 2016	31
BF3	Cowpea	0.01	Dibbling	November 23, 2015	December 27, 2015	34
BF3*	Lettuce	0.01	Transplanting	December 29, 2015	February 19, 2016	52
BF5	Rice	0.08	Transplanting	January 5, 2016	April 28, 2016	114
BF6	Tomato	0.09	Transplanting	September 17, 2015	January 18, 2016	123
Vea irrigation scheme						
VF1	Tomato	0.08	Transplanting	December 27, 2015	n.d.	n.d.
BNF1	Tomato	0.10	Transplanting	January 2, 2016	n.d.	n.d.
BNF2	Roselle	0.05	Dibbling	December 30, 2015	February 17, 2016	49
BoNF2*	Roselle	0.05	Dibbling	February 18, 2016	March 24, 2016	35

** = Second cultivation, ** = Third cultivation, n.d. = not determined*

Appendix 9.14 Summary of crop growth and yield parameters of tomato and details of their measurements in the dry season. The superscripts – ‘t’, ‘m’ and ‘ta’ represents locations of the field in the top, middle and tail sections of the irrigable area.

Parameter	Method of data collection	Frequency of data collection	Cropping field (Figure 3.2)
2014–2015 dry season			
Above-ground biomass	Destructive biomass sampling along a 1 m rod on three selected rows Destructive biomass sampling in two 8 m row sections at harvest	Four times during the vegetative and reproduction stages, and once at harvest time	^{m}BF1, ^{m}BF6, ^{t}VF1, ^{m}BNF1
Plant density	Counting of total number of plants along the 1 m rod on the three selected rows Estimation of the sampling area	Four times during the vegetative and reproduction stages	^{m}BF1, ^{m}BF6, ^{t}VF1, ^{m}BNF1
Leaf area index	Measurements with the SunScan probe (SS1-UM-2.0) at five random locations	Four times during the vegetative and reproduction stages	^{m}BF1, ^{m}BF6, ^{t}VF1, ^{m}BNF1
Row spacing	The average distance between two adjacent rows at five random locations	Once at harvest time	^{m}BF1, ^{m}BF6, ^{t}VF1, ^{m}BNF1
Maximum rooting depth	Manual excavations of at least three plants per crop	Once at harvest time	^{m}BF1, ^{m}BF6, ^{t}VF1
Crop yield	Harvesting and weighing of total tomato fruits from two 8 m row sections	Once at harvest time	^{m}BF1, ^{m}BF6

2015–2016 dry season			
Above-ground biomass	Destructive biomass sampling along a 1 m rod on three selected rows Destructive biomass sampling in two 8 m row sections at harvest	Four times during the vegetative and reproduction stages	^{m}BF1, ^{m}BF6, ^{t}VF1, ^{m}BNF1
Plant density	Counting of total number of plants along the 1 m rod on the three selected rows Estimation of the sampling area	Four times during the vegetative and reproduction stages	^{m}BF1, ^{m}BF6, ^{t}VF1, ^{m}BNF1
Row spacing	The average distance between two adjacent rows at five random locations	Once during the reproduction stage	^{m}BF1, ^{m}BF6, ^{t}VF1, ^{m}BNF1
Maximum rooting depth	Manual excavations of at least three plants per crop	Once at harvest time	^{m}BF1, ^{m}BF6, ^{t}VF1, ^{m}BNF1
Crop yield	Harvesting and weighing of total tomato fruits from two 8 m row sections	Once at harvest time	^{m}BF6, and fields close to ^{m}BF1, ^{t}VF1, ^{m}BNF1

Appendix 9.15 Summary of crop growth and yield parameters of leafy vegetable and details of their measurements in the dry season.

Parameter	Method of data collection	Frequency of data collection	Cropping field (Figure 3.2)
2014–2015 dry season			
Above-ground biomass	Destructive biomass sampling along a 1 m rod on three selected rows Destructive biomass sampling in two 8 m row sections at harvest	Two times during the vegetative and reproduction stages, and once at harvest time	^{m}BF2, ^{m}BF3, ^{m}BNF2
Plant density	Counting of total number of plants along the 1 m rod on the three selected rows Estimation of the sampling area	Two times during the vegetative and reproduction stages	^{m}BF2, ^{m}BF3, ^{m}BNF2
Leaf area index	Measurements with the SunScan probe (SS1-UM-2.0) at five random locations	Two times during the vegetative and reproduction stages	^{m}BF2, ^{m}BF3, ^{m}BNF2
Row spacing	The average distance between two adjacent rows at five random locations	Once at harvest time	^{m}BF2, ^{m}BF3, ^{m}BNF2
Maximum rooting depth	Manual excavations of at least three plants per crop	Once at harvest time	^{m}BF2, ^{m}BF3, ^{m}BNF2
Crop yield	Harvesting and weighing of total above-ground biomass from two 8 m row sections	Once at harvest time	^{m}BF2, ^{m}BF3, ^{m}BNF2
2015–2016 dry season			

Above-ground biomass	Destructive biomass sampling along a 1 m rod on three selected rows Destructive biomass sampling in two 8 m row sections at harvest	Two times during the vegetative and reproduction stages	^{m}BF2, ^{m}BF3, ^{m}BNF2
Plant density	Counting of total number of plants along the 1 m rod on the three selected rows Estimation of the sampling area	Four times during the vegetative and reproduction stages	^{m}BF2, ^{m}BF3, ^{m}BNF2
Row spacing	The average distance between two adjacent rows at five random locations	Once during the reproduction stage	^{m}BF2, ^{m}BF3, ^{m}BNF2
Maximum rooting depth	Manual excavations of at least three plants per crop	Once at harvest time	^{m}BF2, ^{m}BF3, ^{m}BNF2
Crop yield	Harvesting and weighing of total above-ground biomass from two 8 m row sections	Once at harvest time	^{m}BF2, ^{m}BF3, ^{m}BNF2

Appendix 9.16 Summary of crop growth and yield parameters of rice and details of their measurements in the dry season.

Parameter	Method of data collection	Frequency of data collection	Cropping field (Figure 3.2)
2014–2015 dry season			
Above-ground biomass	Destructive biomass sampling in a 1 m^2 (or 0.25 m^2) quadrat at three random locations Destructive biomass sampling in an 8 m^2 section at harvest	Four times during the vegetative and reproduction stages, and once at harvest time	^{t}BF5, ^{t}VF2, ^{m}BoNF2
Plant density	Counting of total number of plants along the 1 m^2 (or 0.25 m^2) quadrat at three random locations Estimation of the sampling area	Four times during the vegetative and reproduction stages	^{t}BF5, ^{t}VF2, ^{m}BoNF2
Leaf area index	Measurements with the SunScan probe (SS1-UM-2.0) at five random locations	Four times during the vegetative and reproduction stages	^{t}BF5, ^{t}VF2, ^{m}BoNF2
2015–2016 dry season			
Above-ground biomass	Destructive biomass sampling in a 1 m^2 (or 0.25 m^2) quadrat at three random locations Destructive biomass sampling in an 8 m^2 section at harvest	Four times during the vegetative and reproduction stages	^{t}BF5
Plant density	Counting of total number of plants in the 1 m^2 (or 0.25 m^2) quadrat at three random locations Estimation of the sampling area	Four times during the vegetative and reproduction stages	^{t}BF5

Maximum rooting depth	Manual excavations of at least three plants per crop	Once at harvest time	[t]BF5
Crop yield	Harvesting and weighing of total rice grains from an 8 m² section	Once at harvest time	[t]BF5

Appendix 9.17 Summary of crop growth and yield parameters of maize and details of their measurements in the rainy season.

Parameter	Method of data collection	Frequency of data collection	Cropping field (Figure 3.2)
Above-ground biomass	Destructive biomass sampling along a 1 m rod on three selected rows Destructive biomass sampling in two 8 m row sections at harvest	Three times during the crop reproduction stage at two weeks interval, and once at harvest time	^{m}BF1, ^{t}VF1, ^{m}BNF1
Plant density	Counting of total number of plants along the 1 m rod on the three selected rows Estimation of the sampling area	Three times during the crop reproduction stage at two weeks interval	^{m}BF1, ^{t}VF1, ^{m}BNF1
Row spacing	The average distance between two adjacent rows at five random locations	Once during the reproduction stage	^{m}BF1, ^{t}VF1, ^{m}BNF1
Maximum rooting depth	Manual excavations of at least three plants per crop	Once at harvest time	^{m}BF1, ^{t}VF1, ^{m}BNF1
Crop yield	Harvesting and weighing of total maize grain yield from two 8 m row sections	Once at harvest time	^{m}BF1, ^{t}VF1, ^{m}BNF1

Appendix 9.18 Summary of crop growth and yield parameters of rice and details of their measurements in the rainy season.

Parameter	Method of data collection	Frequency of data collection	Cropping field (Figure 3.2)
Above-ground biomass	Destructive biomass sampling in a 1 m² (or 0.25 m²) quadrat at three random locations Destructive biomass sampling in an 8 m² section at harvest	Four times during the vegetative and reproduction stages, and once at harvest time	[ta]BF4, [t]BF5, [t]VF2, [m]BoNF2
Plant density	Counting of total number of plants in the 1 m² (or 0.25 m²) quadrat at three random locations Estimation of the sampling area	Four times during the vegetative and reproduction stages	[ta]BF4, [t]BF5, [t]VF2, [m]BoNF2
Maximum rooting depth	Manual excavations of at least three plants per crop	Once at harvest time	[ta]BF4, [t]BF5, [t]VF2, [m]BoNF2
Crop yield	Harvesting and weighing of total rice grains from an 8 m² section	Once at harvest time	[ta]BF4, [t]BF5, [t]VF2, [m]BoNF2

Appendix 9.19 Summary of crop growth and yield parameters of sorghum and millet, and details of their measurements in the rainy season.

Parameter	Method of data collection	Frequency of data collection	Cropping field (Figure 3.2)
Above-ground biomass	Destructive biomass sampling along a 1 m rod on three selected rows Destructive biomass sampling in two 8 m row sections at harvest	Three times during the crop reproduction stage at two weeks interval, and once at harvest time	^{m}BF2, ^{m}BF3, ^{m}BNF2, ^{m}BoNF1
Plant density	Counting of total number of plants along the 1 m rod on the three selected rows Estimation of the sampling area	Three times during the crop reproduction stage at two weeks interval	^{m}BF2, ^{m}BF3, ^{m}BNF2, ^{m}BoNF1
Row spacing	The average distance between two adjacent rows at five random locations	Once during the reproduction stage	^{m}BF2, ^{m}BF3, ^{m}BNF2, ^{m}BoNF1
Maximum rooting depth	Manual excavations of at least three plants per crop	Once at harvest time	^{m}BF2, ^{m}BF3, ^{m}BNF2, ^{m}BoNF1
Crop yield	Harvesting and weighing of total maize grain yield from two 8 m row sections	Once at harvest time	^{m}BF2, ^{m}BF3, ^{m}BNF2, ^{m}BoNF1

Appendix 9.20 Pictures of (a) a meeting with farmers, (b) a geodetic survey for elevation-volume-area curves in Bongo, water level measurements in (c) groundwater well, (d) irrigation canal, and (e) reservoir, (f) ponding test.

(a)

(b)

(c)

(d)

(e)

(f)

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