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Soil water availability in agriculturally used wetlands of East Africa

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To my family

Contents

List of Abbreviations

a_0	offset of regression equation
a_1	slope of regression equation
α	level of significance (statistics)
α	inverse of the air-entry value (HYDRUS-1D)
AEZ	agroecological zone
ANOVA	analysis of variance
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
Bc.	boundary condition
C	carbon
CV	coefficient of variation
DEM	digital elevation model
df	degrees of freedom
DIN	Deutsches Institut für Normung
ϵ	permittivity
EM-sensors	electromagnetic sensors
ET	evapotranspiration
ET_a	actual evapotranspiration
ET_p	potential evapotranspiration
G_i	capillary rise
G_o	groundwater recharge
F	F-distribution
f	infiltration rate
FAO	Food and Agriculture Organization of the United Nations
FC	field capacity
FDR	Frequency Domain Reflectometry
GWF	groundwater flow
GWL	distance of groundwater table to ground surface
GR4J-model	modèle du Génie Rural à 4 paramètres Journalier
h	water pressure head
HBV-model	Hydrologiska Byråns Vattenavdelning-model
HGM	hydrogeomorphic
IF	interflow
IIASA	International Institute for Applied Systems Analysis

IQR	interquartile range
IWM	Integrated Watershed Management
K	hydraulic conductivity
K_s	saturated hydraulic conductivity
l	tortuosity parameter
LAI	leaf area index
LDS	long dry season
LGP	length of growing period
LRS	long rainy season
LULC	land use/land cover
m	mean
m a.s.l.	meters above sea level
N	nitrogen
n	sample size (statistics)
n	pore-size distribution index (HYDRUS-1D)
NASA	National Aeronautics and Space Administration
nd	normal distribution
NSE	Nash-Sutcliffe model efficiency coefficient
NWCS	National Wetland Classification System
OC	organic carbon
OF	overland flow
P	precipitation
p	significance value
PWP	permanent wilting point
R^2	coefficient of determination
R_a	extra-terrestrial radiation
ρ_S	bulk density of soil
ρ_W	density of water
$r.H.$	relative humidity
$RMSD$	root mean squared difference
$RMSE$	root mean squared error
r_s	Spearman's rank-order correlation coefficient
RU	Surface runoff
s	standard deviation
$S(h)$	water sink term
ΔS	change in storage
S_e	effective soil water saturation

SD	stream discharge
SDS	short dry season
SM	soil moisture
SO	spill-over
SRS	short rainy season
SRTM	Shuttle Radar Topographic Mission
t	time
t	t-distribution
TDR	Time Domain Reflectometry
θ	volumetric soil water content
θ_G	gravimetric soil water content
θ_R	residual soil water content
θ_S	saturated soil water content
TIN	Triangulated Irregular Network
T_m	daily mean air temperature
T_R	temperature range between the mean daily maximum and minimum air temperature
UNEP	United Nations Environmental Program
USDA	United States Department of Agriculture
VBR	valley bottom ratio
WCG	Wetland Cluster Group
WMO	World Meteorological Organization of the United Nations
z	vertical coordinate axis

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Summary

Wetlands contribute increasingly to the food needs and income generation of the rural population in East Africa. The transformation of wetlands into farmland has gained momentum due to a growing food demand, upland shortages and increasing climate variability. A wetland's agricultural production potential is largely determined by its soil fertility as well as the water availability in the rooting zone of crops.

In this Dissertation, I assessed the spatial and temporal soil water availability, and related moisture status to hydrogeomorphological conditions and types of land use. Based on an initial classification of wetlands in the region, the present work focussed on two representative agriculturally used wetlands. Tegu is an inland valley wetland of about 10 ha in the humid tropical highlands (1720 m a.s.l.) south of Mount Kenya, Kenya. Malinda is a floodplain located in the plains of Mkomazi River in the sub-humid tropical lowlands (360 m a.s.l.) at the western leeward side of the Usambara Mountains, Tanzania. While both sites are mainly used for crop production, unused portions remain under natural wetland vegetation.

Hydrometeorological state variables, comprising Frequency Domain Reflectometry (FDR)-based soil moisture contents, groundwater levels and stream discharge, were monitored between 2009 and 2011. Thereby, different landscape positions and land use types in the wetlands were covered. A site-specific calibration procedure for the FDR system yielded a higher measurement accuracy for the Tegu site than that achieved using the manufacturer's calibration function.

Groundwater level and the duration of soil saturation were closely related to the landscape position along and across the Tegu inland valley, thus determining the suitability of specific locations within the wetland for crop cultivation. In the bowl-shaped valley head with no pronounced stream channel, the cultivation of forage grass (*Pennisetum purpureum*) prevailed. In the floodplain-like lower section with an extensive network of drainage/irrigation channels, taro *(Colocasia esculenta)* was widespread and generally cultivated in association or rotation with upland crops, mainly maize *(Zea mays)* and vegetables. The Tegu valley bottom is agriculturally used although soil moisture contents are often too high, which bears the risk of crop failure due to flooding. The application of a semi-distributed rainfall-runoff model yielded an overestimation of the stream discharge during the long dry season of the hydrological year 2010/2011, indicating the impact of water abstraction for irrigation.

In the Malinda floodplain, soil moisture measurements were conducted for a) natural vegetation, b) dry season grazing land, c) rainfed and irrigated rice plots, and d) upland crop fields. The shrink-swell-behaviour of the Vertisols impeded the application of the FDR sensor, as well as the determination of hydraulic soil properties. The length of the growing period as derived from HYDRUS-1D daily soil water balances ranged from 115 days in the fringe areas to 243 days in areas with prevailing shallow groundwater tables. Thus, agricultural land use and crop production potential, as determined from the period of crop-specific soil water storage, depend largely on the dominant water source (groundwater, surface water).

The outcomes of the Dissertation can guide appropriate land use planning for a sustainable wetland use reconciling the increasing demand for agricultural products with the need to respect environmental concerns and to preserve ecosystem services.

Zusammenfassung

Feuchtgebiete leisten einen zunehmend wichtigen Beitrag zur Ernährungssicherung und der Erwirtschaftung von Einkommen für die ländliche Bevölkerung in Ostafrika. Die Umwandlung von Feuchtgebieten in Ackerland wird durch den wachsenden Bedarf an Nahrungsmitteln, die Verknappung an Flächen für den Trockenfeldbau und eine zunehmende Veränderlichkeit des Klimas beschleunigt. Neben der Bodenfruchtbarkeit bestimmt dabei die Wasserverfügbarkeit in der Wurzelzone von Ackerfrüchten das landwirtschaftliche Produktionspotential von Feuchtgebieten.

In der vorliegenden Promotionsarbeit wurde die räumliche und zeitliche Verfügbarkeit von Bodenwasser untersucht und in Beziehung zu hydrogeomorphologischen Bedingungen und Landnutzungstypen gesetzt. Die Arbeit wurde in zwei repräsentativen landwirtschaftlich genutzten Feuchtgebieten durchgeführt, deren Auswahl auf einer umfassenden Kategorisierung von Feuchtgebieten in der Region basierte. Tegu ist ein Inlandtal im tropisch-feuchten Hochland (1720 m NN) südlich des Mount Kenya in Kenia mit einer Fläche von etwa 10 ha. Die Malinda Überschwemmungsfläche befindet sich in den Ebenen des Mkomazi Flusses im tropischen sub-humiden Tiefland (360 m NN) an der westlichen, leewärtigen Seite der Usambara Berge in Tansania. Beide Standorte werden überwiegend ackerbaulich genutzt, wobei auch noch weitgehend ungestörte Restflächen mit natürlicher Feuchtgebietsvegetation existieren.

Hydrometeorologische Zustandsgrößen, einschließlich FDR (Frequency Domain Reflectometry)-basierter Bodenwassergehalte, Grundwasserflurabstände und Durchfluss, wurden zwischen 2009 und 2011 gemessen. Dabei wurden verschiedene Reliefpositionen und Landnutzungstypen innerhalb der Feuchtgebiete unterschieden. Eine standortspezifische Kalibrierung des FDR-Sensors lieferte eine höhere Messgenauigkeit für das Inlandtal als die Kalibrierungsfunktion des Herstellers. Grundwasserflurabstand und die Dauer der Bodensättigung standen in Beziehung zu der Reliefposition im Längs- und Querprofil des Inlandtales und bestimmten damit die Standorteignung für ackerbauliche Nutzung. In dem kesselförmigen Talkopf ohne ausgeprägtes Flussbett herrschte der Anbau von Futtergras (*Pennisetum purpureum*) vor. Der untere Talabschnitt, der einer Überschwemmungsebene ähnelt, war durch ein ausgeprägtes Netz an Be- und Entwässerungskanälen gekennzeichnet und wurde vorwiegend für den Anbau von Taro (*Colocasia esculenta*), üblicherweise im Mischanbau oder in einer Fruchtfolge mit Trockenlandkulturen (*Zea mays*) sowie diversen Gemüsearten genutzt. Für diese Art der Landnutzung ist der Boden allerdings verbreitet zu feucht, was das Risiko von Überstau-bedingten Ernteausfällen mit sich bringt. Die Anwendung eines semi-distributiven Niederschlags-Abfluss Modells ergab eine Überschätzung des Abflusses während der langen Trockenzeit des hydrologischen Jahres 2010/2011, was auf den Einfluss der Entnahme von Bewässerungswasser zurückzuführen war.

In der Malinda Überschwemmungsebene wurden Bodenfeuchtemessungen an Standorten mit a) natürlicher Vegetation, b) Beweidung während der Trockenzeit, c) Nassreis im Regen-abhängigen sowie im Bewässerungsanbau, und d) dem Anbau von Trockenlandkulturen durchgeführt. Das Schwellungs-Schrumpfungs-Verhalten der Vertisole erschwerte den Einsatz des FDR-Sensors ebenso wie die Ermittlung bodenhydraulischer Kenngrößen. Die Länge der Wachstumsperiode wurde basierend auf Ergebnissen der täglichen Bodenwasserhaushaltsbilanzierung in HYDRUS-1D bestimmt und lag zwischen 115 Tagen im Randbereich der Ebene und 243 Tagen in Gebieten mit geringen Grundwasserflurabständen. Das landwirtschaftliche Nutzungspotential, welches über die verfügbare Dauer Kultur-abhängiger Bodenwasservorräte ermittelt wurde, hing in hohem Maße von der Art der Wasserquelle ab (Grund-/Oberflächenwasser).

Die Ergebnisse der Dissertation können bei der Planung einer nachhaltigen Feuchtgebietsnutzung herangezogen werden, welche sowohl dem zunehmenden Bedarf an landwirtschaftlichen Produkten wie auch dem Naturschutz und dem Erhalt ökosystemarer Dienstleistungen Rechnung trägt.

Chapter 1

Wetlands in East Africa

1.1 Introduction

Wetlands are transitional lands possessing characteristics of both terrestrial and aquatic ecosystems, whereby wet and dry conditions can alternate rapidly. Wetlands are multi-functional and supply provisioning, regulating, cultural and supporting ecosystem services. The provision of these services depends strongly on the type of wetland ecosystem (Millenium Ecosystem Assessment Board, 2005). The availability of water and the relatively high fertility of the soils make wetlands potential areas for agricultural production (Frenken and Mharapara, 2002), which occurs often at the detriment of other ecosystem services.

1.1.1 Definition, characterization and distribution of wetlands

One of the most widely accepted definitions of the term "wetland" is that of the Convention on Wetlands of International Importance ('Ramsar Convention') (Ramsar Convention Secretariat, 1994), according to which "wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres". Wetlands "may incorporate riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six metres at low tide lying within the wetlands".

Generally, two geomorphological prerequisites are necessary for the creation of a wetland: Sufficient water must be provided (hydrologic condition) and the topographic situation must permit the retention of water at or close to the surface, such as through a flat relief and impermeable layers (Nyamweru, 1992).

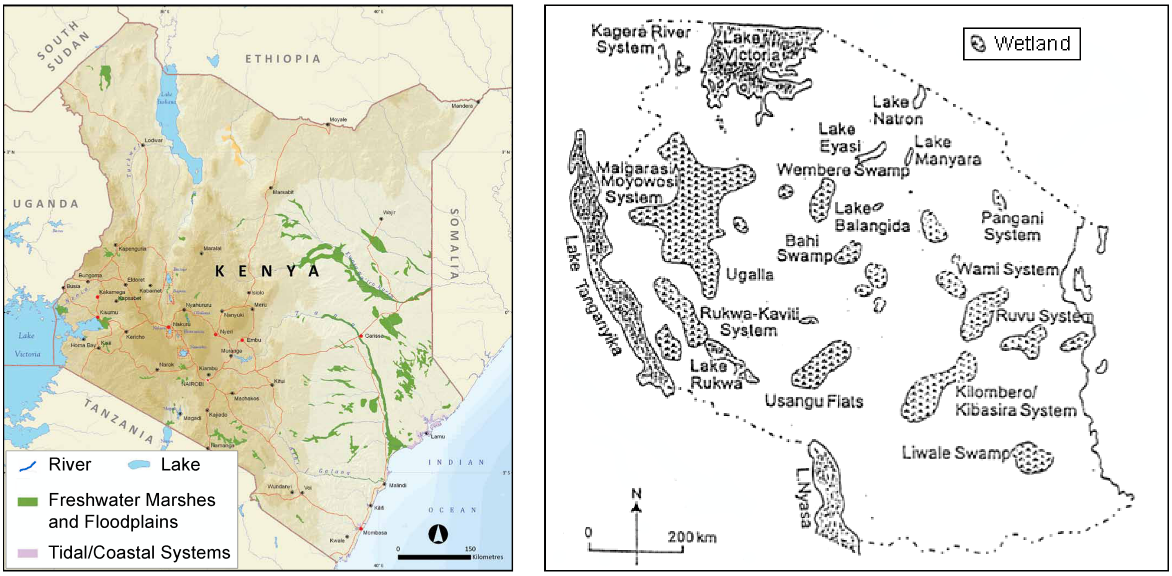
Internationally, numerous wetland classification systems exist. Thereby, it is possible to distinguish between two different approaches, although these may also be combined: a) geographically-based classification systems and b) classification systems which rely on environmental characteristics that determine the wetland status (U.S. Environmental Protecton Agency, 2008). Wetlands can be classified biologically, physically, chemically, and hydrogeomorphically, thus using information on landscape position, landform, land use and vegetation, hydrology, water chemistry, nutrient status and soil types (Tiner, 2009).

Cowardin et al. (1979) developed a hierarchical system which was devised to inventory the wetlands and deepwater habitats of the United States. This classification is based on vegetation (hydrophytes), soils/substrate material (hydric soils) and the frequency of flooding. The classification system of the Ramsar Convention is a modification of Cowardin's system which allows for the rapid identification of the main wetland habitats represented at Ramsar sites (Scott and Jones, 1995).

Brinson (1993) emphasized the link between wetland hydrology, geomorphology and wetland functions and created a wetland classification scheme based on geomorphic setting, water source and hydrodynamics. The geomorphic approach of Semeniuk and Semeniuk (1995) to classify inland wetlands was initially designed for the region of southwestern Australia and focuses on landform shape and type of hydroperiod. The National Wetland Classification System (NWCS) of South Africa follows the hydrogeomorphic (HGM) approach and uses hydrological and geomorphological characteristics for wetland classification.

In Kenya, the area of freshwater wetlands comprises between 3 to 4 percent of the country's surface area (National Environment Management Authority Kenya, 2009) (Figure 1.1). Approximately 13 percent of Uganda's and 10 percent of Tanzania's country area are covered by wetlands (Kamukala, 1993; Uganda National Environment Management Authority, 2009). Tanzania has designated four wetlands as internationally important Ramsar sites, Kenya six, and Uganda 12, respectively (Ramsar Convention Bureau, 2015).

Most classification systems applied in the East African region are also related to the Ramsar scheme. In Kenya, the existence of six wetland types from the Ramsar classification system (Ramsar Convention Secretariat, 1994) has been reported (Kenya Ministry of Environment and Mineral Resources and UNEP, 2012); riverine, lacustrine, palustrine, estuarine, marine, and constructed wetlands. Inland or freshwater wetlands represent the major proportion of the wetland area (96%). In Tanzania, the same wetland types are described as for Kenya (Kamukala and Crafter, 1993). Due to its interior location in Eastern Africa, Uganda does not have marine and estuarine wetlands, but extensive wetlands areas around lakes and along rivers.



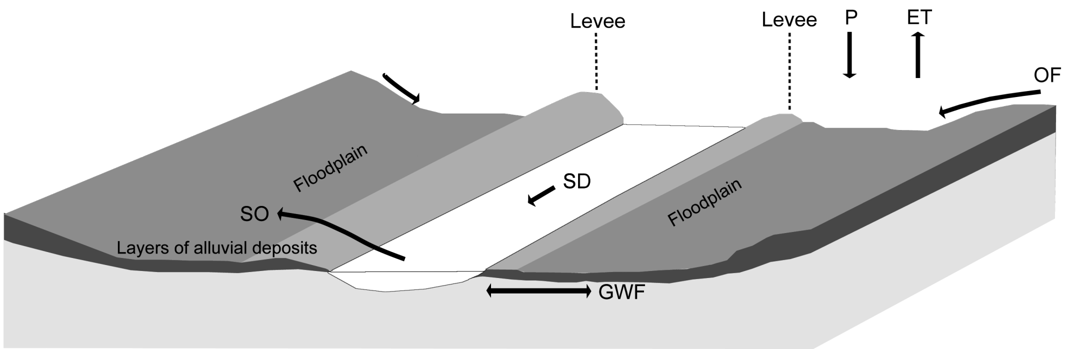
(a) (b)

Figure 1.1: Distribution of natural wetlands in East Africa: (a) Example Kenya. Adopted from National Environment Management Authority Kenya (2011); (b) Example Tanzania. Source: Kalinga and Shayo (1998)

In the following, a brief description of the two wetland types, on which this thesis focuses, is provided.

On the one hand, the floodplains of the alluvial lowlands are formed by rivers with large variations in discharge which inundate adjacent low-lying areas in times of high-water by out-of-bank flooding (Roggeri, 1995) (Figure 1.2(a)). On flat terrain, seasonal rains cause flooding on impermeable soils. Fluvial features, such as elevated levees and low-lying, semi-permanently flooded backswamps may occur.

On the other hand, inland valley wetlands are defined as the "upper reaches of river systems, comprising valley bottoms and minor floodplains which may be submerged for part of the year, their hydromorphic fringes, and contiguous upland slopes and crests" (Andriesse et al., 1994, p.159) (Figure 1.2(b)). They are also called "headwater lowlands" (Roggeri, 1995) and are found where runoff, subterranean flows and groundwater meet. Raunet (1985) (in Windmeijer and Andriesse, 1993) distinguishes between three parts along the valley: a) the valley head where there is no stream channel and colluvial processes dominate; b) the wider midstream part of the valley where, despite there being a shallow stream channel, colluvial processes continue to dominate and c) the downstream part of the valley with alluvial soils and river flooding.



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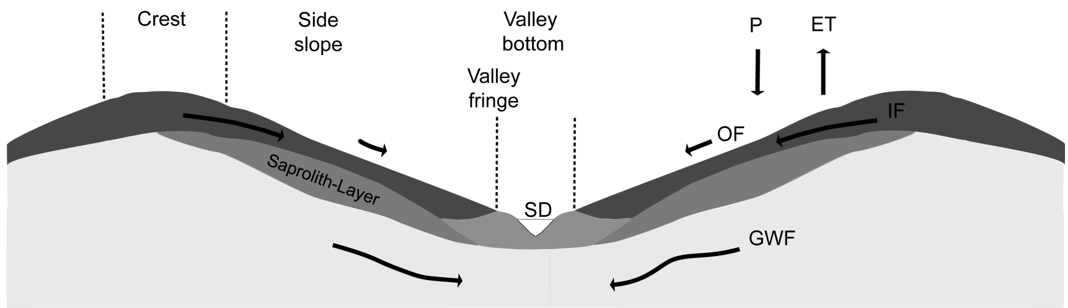


(b)

Figure 1.2: Hydrological components of two typical wetland types in East Africa. *P*=Precipitation, *ET*=Evapotranspiration, *OF*=Overland flow, *IF*=Interflow, *GWF*=Groundwater flow, *SD*=Stream discharge, *SO*=Spill-over: (a) Floodplain wetland; (b) Inland valley. Adopted from Windmeijer and Andriesse (1993).

1.1.2 Uses of wetlands and impacts of agriculture

In particular, palustrine and riverine wetland systems are considered suitable for agricultural development (Frenken and Mharapara, 2002). The management practices applied by wetland communities in Africa have evolved over long periods of time and have ensured the sustainable use of wetland resources (Palela, 2011; Wood et al., 2002). Farmers have gained knowledge of the soil conditions and hydrological regimes of these areas. As an example, cultivation on raised beds to avoid waterlogging of the rooting zone of crops was reported for the poorly-drained areas of Nyandarua District (Central Province, Kenya) in the late 1950s and early 1960s (Gichuki, 1992). Wetlands contribute substantially to the food needs of the rural population and to the generation of income, such as from fishing, agriculture, the sale of building materials and fuelwood, hunting and tourism (Abila, 2002). In Kajiado, Kenya, wetlands contribute up to 40% of the total income generated from local natural resources although they only cover 2% of the district's surface area (Government of Kenya, 1996 in Gichuki et al., 2001).

With increasing climate variability and the declining availability and quality of upland areas for agricultural production (Maitima et al., 2009; Wood and van Halsema, 2008), communities in Africa increasingly depend on wetland resources, especially during the 'hungry' season (Dixon and Wood, 2003). An increasing demand for agricultural land (Mohamed, 2002) to feed a rapidly growing population is seen as further accelerating the conversion of wetlands into sites of agricultural production (Junk, 2002). The projected climate change scenarios, particularly the increased spatial-temporal variability of precipitation (Collins et al., 2013; Giannini et al., 2008), may accelerate such trends. Yet, they also highlight the increasing importance of the role that the wetlands will play as buffer systems in the future (Wood and van Halsema, 2008).

Large and well-known wetlands - particularly those of international importance, such as the Tana River Delta and Lake Naivasha in Kenya (Awange et al., 2013; Leauthaud et al., 2013) or Lake Victora in Tanzania (Mwakubo and Obare, 2009) - have received much attention of researchers. However, small wetlands of just a few hectares size have been largely neglected, despite these being much more abundant and covering a much larger area (Mwita et al., 2013; Stevenson and Frazier, 2001). It has been hypothesized that these small wetlands have the potential to become the future food baskets of the region (Dixon and Wood, 2003) and that this development will be further supported by new technologies and crop varieties (Wood et al., 2002), as well as government policies (Abila, 2002).

At a larger scale, floodplain wetlands are the focus of agricultural development (irrigation) projects due to their water availability, large size and high abundance in the region. The Southern Agricultural Growth Corridor in Tanzania, which includes the Kilombero valley wetland, covers approximately one-third of Tanzania's mainland and is "designed to improve agricultural productivity, food security and livelihoods in Tanzania" (Southern Agricultural Growth Corridor of Tanzania, 2014).

Despite being important areas of agricultural resources in both the present and for the future, wetlands are increasingly threatened by overuse and inappropriate usage involving large-scale drainage measures (Galbraith et al., 2005). The drainage of wetland soils, which are often characterized by an accumulation of incompletely decomposed organic matter, may trigger the decrease of organic matter following soil aeration. This would enhance emissions of CO_2 and affect the water-holding capacity and structure of wetland soils.

Thus, wetland conversion following large-scale drainge measures may be of short-term benefit, yet the negative effects on the hydrological cycle, soil quality and other system components are likely to make a long-term impact. Eventually, such alterations can lead to a degradation of the wetland ecosystem (Kotze, 2011). Consequently, wetlands may loose the potential to provide valuable services to communities. Gichuki (1995) estimated a 7% annual loss of wetlands in Kenya primarily due to drainage for agriculture.

The awareness of the various functions and services wetlands provide has fueled an approach to wetland conservation that has mainly been driven by environmental concerns regarding the previously mentioned negative impacts of wetland (over)use. This approach has resulted in attempts to exclude wetland pastoralists (Lankford et al., 2004). However, there has recently been a "paradigm shift" towards a "people-centered wetland management" (Wood et al., 2013, p.4-5).

This new orientation entails reconciling the need for food production with concerns about the preservation of vital ecosystem services. The awareness is rising that it is necessary to preserve "critical wetlands" in protected areas. However, the majority of wetlands remains outside of such areas. They may be transformed carefully and at different intensities for "wise" uses, while simultaneously benefiting from traditional knowledge of wetland communities, as well as modern management strategies and technologies.

1.1.3 (Soil) water availability in wetlands

The planning and management of wetland systems requires an understanding of their hydrological functioning. The issues presently being addressed are the assessment of the impacts of water abstraction, the conversion of wetlands or land-use changes in the catchment. In this context, the type of wetland, its topographic situation and the source of water determine the hydrological research design and, accordingly, its temporal and spatial scale and resolution.

Various examples of hydrological wetland research in the Southeast African region exist. Kashaigili (2008), for instance, studied river flow to understand the impacts of land-use changes on hydrological flow regimes for the Usangu wetland and the Great Ruaha River in Tanzania. Based on findings from a papyrus wetland in western Kenya, van Dam et al. (2013) investigated the relationships between hydrology, ecosystem function and livelihood outcomes. In addition, water table fluctuations have been interpreted with respect to wetland use regimes in Illubator, Ethiopia (Dixon and Wood, 2003). Furthermore, evapotranspiration rates which were calculated based on remotely-sensed data for the Kilombero River Basin in Tanzania have indicated the impacts of wetland conversion on the system's water balance (Munishia and Jewitt, 2014).

The role of dambo wetlands, a wetland type which is widely distributed in Southern and Central Africa, in the hydrological cycle has been intensively studied (Acres et al., 1985; Bullock and Acreman, 2003). Dambos are characterized by permanently or seasonally waterlogged conditions and open herbaceous vegetation and they are located in valleys, depressions, or floodplains. The frequently cited importance of dambos for flood retention and the maintenance of dry-season river flow (Balek and Perry, 1973), as well as the negative impact of the agricultural use of these systems on stream discharge, remains a topic of heated discussion (McCartney et al., 2010; von der Heyden and New, 2003).

From an agronomic perspective, water availability in wetland soils is the most important hydrological attribute, determining the agricultural production potential both directly (Worou et al., 2012) and indirectly by controlling nutrient dynamics (Bai et al., 2004). Evapotranspiration from the unsaturated zone constitutes a considerable part of a wetland's water balance (Baker et al., 2009). Crop yields depend largely on water availability in the rooting zone (FAO, 2012). Thus, the amount of residual moisture available in wetland soils is important for providing food-security (Bosekeng et al., 2012; Mati, 2006) and the duration of the growing period may be extended as compared to adjacent upland sites. The soil moisture status of wetland soils is influenced by soil-physical properties and climatic conditions.

Land and water management practices in the wetland and its catchment have an effect on soil moisture as well as the valley morphology which controls runoff and infiltration (Georgakakos and Baumer, 1996). Therefore, soil water availability does not only determine a wetland's suitability for agricultural production, but, at the same time, it can serve as an indicator for impacts on the system's hydrological regime. Consequently, monitoring the amount and the dynamics of soil moisture requires increased research attention in the face of wetland conversion into sites of agricultural production.

1.1.4 Modelling the dynamics of water availability in wetlands

Various factors can lead to an abundance of gaps in the time series of soil moisture measurements. In order to overcome this limitation, soil water models may provide solutions. HYDRUS-1D (Šimůnek et al., 2008) has been widely applied to describe the interactions between meteorological conditions, land cover and seasonal soil water storage.

Joris and Feyen (2003) described the application of a two-dimensional version of HYDRUS on a riparian wetland in Belgium. A wetland simulation module for MODFLOW groundwater model was developed for the purpose of simulating wetland flow hydroperiods and wetland interactions with aquifers and channels (Restrepo et al., 1998). This module has been utilized to study depth-to-water table and water table fluctuations at a wet coastal grassland in Sussex, UK, on which ditch water levels were regulated. During this study, special attention was paid to the conservation of important wetland habitats (Bradford and Acreman, 2003).

Lumped rainfall-runoff models with few parameters, such as GR4J (Perrin et al., 2003), represent the effective response of a wetland's entire catchment, e.g. to climate and land use changes (Troy et al., 2007). Lumped rainfall-runoff models are widely applied in data scarce environments. However, unlike physically-based distributed models, they are not capable of considering the spatial variability of the catchment's response (Legesse et al., 2003). Giertz et al. (2006) applied a distributed model in a headwater catchment in Benin to simulate hydrological processes. Unami et al. (2009) conducted numerical simulations of floods within single rainfall events in the Ghanaian inland valleys. In the research conducted by Helmschrot et al. (2005) in Eastern Cape Province, South Africa, dominant processes and the dynamics of water flow into and through wetland bodies were identified and simulated with the Precipitation-Runoff Modelling System (PRMS). These examples underline the suitability of hydrological models for the simulation of impacts of land and water management practices on the dynamics of water availability in wetlands and their catchment areas.

1.1.5 Research questions and objectives

The thesis aims to determine the temporal and spatial availability of water - particularly plant available soil water - for agricultural production in wetlands. The following research question guided the study:

How much water is available in a) an inland valley swamp and b) a floodplain wetland, and how does the availability vary in space and time?

Sub-questions can be formulated as follows:

- How does the morphology of a wetland control the soil water availability and which other factors may play a role?
- How are agricultural production potential and current land use and land cover (LULC) related to the water availability in these two wetland types?

To address these questions, the following research objectives were formulated:

- describe the biophysical characteristics of two wetland types in different climatic zones, including meteorological variables, water sources (surface water, sub-surface water), geomorphic setting, and soil attributes,
- describe patterns of land use and land cover for two wetland types,
- assess the spatial and temporal variations in volumetric soil moisture content in the rooting zone of the representative sites using a capacitance soil moisture sensor,
- relate seasonal soil water storage to meteorological conditions, landscape position and types of land use and land cover and
- draw conclusions on the suitability of the two wetland types for crop production.

To achieve these goals, I combined *in-situ* measurements of hydrometeorological state variables with field surveys of land use and topography and the application of hydrological models. The outcomes of this research will contribute to a scientifically-based characterization of the agro-ecosystems of wetlands in East Africa from a hydrological perspective.

1.1.6 Project framework

This research was conducted within the framework of two projects: the IWMNet-project and the SWEA-project. One major component of the IWMNet-project "Capacity Building for Integrated Watershed Management (IWM) in Eastern Africa" was the support of research activities related to IWM which were conducted by the partnering universities. It was funded under the 9^{th} European Development Fund (EDF), ACP-EU Water Facility.

The project "Agricultural Use and Vulnerability of Small Wetlands of East Africa (SWEA)" received funding from the Volkswagen Foundation in Hannover, Germany. The specific research objectives of SWEA were (1) to capture the current diversity of wetlands in terms of types and their spatial distribution and to define the driving forces of change and/or use. Thus, a wetland typology had to be developed; (2) to determine the potential of wetlands as sites of biodiversity and providers of ecological functions; (3) to determine the dynamics and availability of carbon, nutrients and water and to link the underlying processes with production potential; (4) to quantify factor interactions and develop a model for scenario evaluation and extrapolation. Based on the findings, strategies for reconciling wetland conservation with changing human needs are being developed. The Dissertation mainly addresses research objectives (1) and (3) from a hydrological perspective.

1.2 General materials and methods

1.2.1 Study sites

The present work focuses on two riverine wetlands: a floodplain wetland in Tanzania and a valley bottom wetland in Kenya. Both sites are considered representative for the region according to a typological work conducted by Sakané et al. (2011) on Kenyan and Tanzanian wetland sites (Chapter 2). This study yielded five wetland cluster groups (WCG) comprising "(1) narrow permanently flooded inland valleys that are largely unused; (2) wide permanently flooded inland valleys and highlands floodplains under extensive use; (3) large inland valleys and lowland floodplains with seasonal flooding under medium use intensity; (4) completely drained wide inland valleys and highlands floodplains under intensive food crop production; and (5) narrow drained inland valleys under permanent horticultural production." The narrow inland valley wetland of Tegu in Kenya combines characteristics of cluster group WCG 1 and WCG 4. Malinda floodplain wetland in Tanzania is representative for WCG 3. However, some portions exhibit characteristics of WCG 1. For a detailed description of the two study sites, the reader is referred to chapters 2, 3, 4 and 5.

Geographical location

The inland valley wetland of the Tegu Stream is located in the humid highlands south of Mount Kenya in Nyeri County, which was formerly part of the Central Province of Kenya (Figure 1.3). The Karatina municipality is located about 2.5 km away on the Nyeri-Nairobi highway which passes through the area.

The Malinda floodplain is part of the plains of the Mkomazi River at the western, lee-ward side of the Usambara mountains in the Tanga region of the Korogwe District of Tanzania. It is located along the Arusha-Dar es Salaam highway between Mombo and Korogwe. The catchment of the Tegu Stream is part of the basin of Tana River, the largest river in Central Kenya. The Mkomazi River is a tributary to the Pangani River which rises on Mount Kilimanjaro and flows over 500 km before draining into the Indian Ocean.

Biophysical characteristics

To more easily compare the two study sites, a brief summary of their most important biophysical characteristics is provided in Table 1.1.

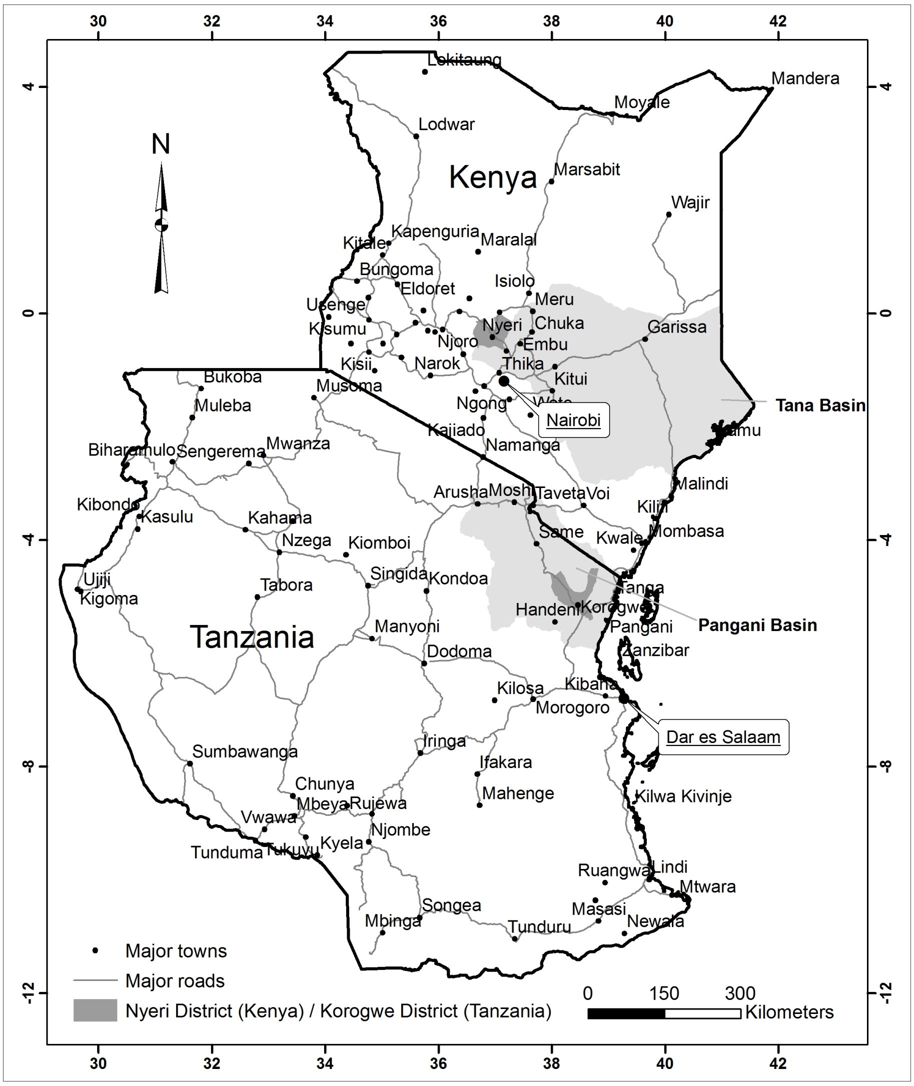


Figure 1.3: Location of the two study sites; Tegu inland valley, Kenya, Malinda floodplain, Tanzania. Map data from African Development Bank Group (2015); Map Library (2013); World Resources Institute (2014).

Table 1.1: Summary of biophysical characteristics of the two study sites in Kenya and Tanzania. LGP=Length of growing period and AEZ=Agro-ecological zone as per definition of Fischer et al. (2012). *=data differ slightly from Chapter 3 due to re-measurements, **=data differ slightly from Chapter 4 due to re-measurements

Parameter	Tegu inland valley	Malinda plains	Source of information
Longitudinal extent	37°6'1"-37°6'32"E*	38°19'16"-38°21'36"E	own measurement
Latitudinal extent	0°27'14"-0°28'49"S*	5°4'29"-5°7'14"S	own measurement
Elevation [m a.s.l.]	1720 (valley bottom) -1830(ridge)*,**	360 (floodplain) -1320 (uplands)	(Ordnance Survey of the UK, 1988; Survey of Kenya, 1974)
Topography	strongly undulating mountain slopes, concave longitudinal and cross-sectional profile	flat-gently undulating gilgai relief	-
Main stream/river	Tegu Stream	Mkomazi River	
Major river basin	Tana	Pangani	-
Wetland size [ha]	10*	1,100	-
Sub-catchment area [ha]	230*	32,100	-
Climate	humid, rainfall 1450 mm/yr, bimodal rainfall pattern, average temp. 15-20° C	sub-humid, rainfall 1074 mm/yr, bimodal rainfall pattern with unreliable onsets, average temp. >20° C	(Alvarez et al., 2012; Jaetzold et al., 2006), Korogwe rainfall station, Nyeri meteorological station
Thermal climate	Tropical highland	Tropical lowland	(Fischer et al., 2012)
LGP [days]	240-269	180-209	(FAO and IIASA, 2014)
Geology	Pleistocene Mt. Kenya volcanic series	Superficial unconsolidated alluvial sediments of quarternary age	(Agrar- und Hydrotechnik GmbH, 1976b; Baker, 1967)
Wetland soils	Dystric Fluvisol	Vertisol, Fluvisol, Gleysol	(Agrar- und Hydrotechnik GmbH, 1976b; FAO, 2003; Njoroge and Macharia, 2009)
Upland soils	Nitisol	Ferralsol	(FAO, IIASA, ISRIC, ISSCAS, JRC, 2012; FAO, 2006)

According to Köppen climate classification, both study sites are assigned a tropical savannah climate (Aw), whereby Tegu is characterized by a cooler climate than Malinda (Figure 1.4). No data for the 30 year reference period (1961-1990) are available. The meteorological station in Nyeri, Kenya (Figure 1.4(a)), is located at approximately 18 km linear distance northwest of Tegu valley. Average rainfall of the period 1979 to 2009 was remarkably lower (966 mm) than for the Tegy study site in 2010 (1489 mm) (Figure 1.4(c)). It must be emphasized that rainfall during the long, rainy season 2010 (March-June) was strikingly high. Yet, average annual temperature was in the same order.

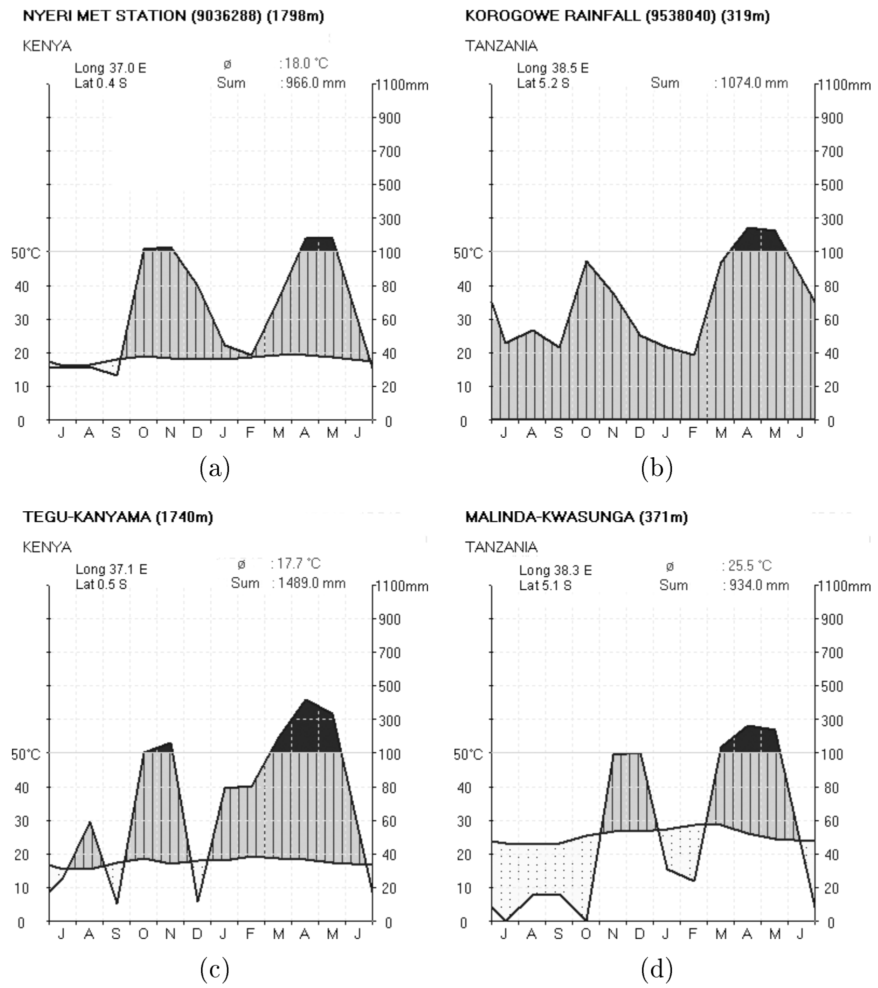


Figure 1.4: Diagrams of monthly rainfall and air temperature for the study areas in Kenya and Tanzania. Vertical lines mark humid months. Exaggeration of right Y-axis above 100 mm. (a) Nyeri Meterological station (No. 9036288). Diagram based on measurements between 1992 and 2009 (temperature) and between 1979 and 2009 (rainfall). Data gaps encountered in time series; (b) Korogwe rainfall station (No. 9538040). Diagram based on measurements between 1970 and 2009. Data gaps encountered in time series; (c) Tegu inland valley. Diagram based on own measurements from 2010. Due to the malfunctioning of the temperature sensor in May 2010, data from May 2011 is given; (d) Malinda floodplain. Diagram based on own measurements from 2010.

The rainfall station in Korogwe town, Tanzania, at about 18 km linear distance south-east of our station at Malinda-Kwasunga, can be considered to be representative for the Mkomazi plains (Figure 1.4(b)). Average rainfall for the period 1970-2009 was 1074 mm, which is slightly above the annual rainfall in Malinda floodplain in 2010 (934 mm) (Figure 1.4(d)). Long term temperature data have been collected only in Lushoto. Due to its location in the Usambara mountains (1383 m a.s.l.) the station does not represent the climatic conditions of the Malinda floodplain.

Land use and land cover

Cropland is the dominant land use category of both wetland types. Taro (*Colocasia esculenta*) is cultivated under flooded conditions in the Tegu inland valley wetland. Maize (*Zea mays*) and beans (*Phaseolus vulgaris*) are common food crops which are cultivated partially in rotation or in combination with taro. Wetland farmers have established a network of small canals in the flat parts of the valley bottom which serves two purposes: plot drainage during the rainy season and supplementary irrigation during the dry season. Some portions of the valley bottom are covered with natural wetland vegetation (mainly *Cyperus* spp.). Zero grazing is common in the area, whereby the cattle are confined in one place and fodder, often comprising napier grass from the valley, is brought to the animals. Thus, only a small part of the wetland is allocated for cattle grazing. Furthermore, coffee trees (*Coffea robusta*) are cultivated on the adjacent uplands.

In the central portion of the Malinda plains, a system of ridges and channels allows for the production of lowland rice during the long rainy season (pluvial rice cropping system). Wet rice cropping systems are established where spring water is available. Communal grassland with shrubs and trees at varying densities is utilized for dry season grazing (nomadic herding). Moreover, “slash and burn” farming and bush fallow rotation are commonly practiced. The cash crops are lady finger, paprika, and tomato. Cyperaceae (e.g. *Cyperus papyrus*) and Typhaceae (*Typha domingensis*, *Typha capensis*) dominate areas under permanently flooded conditions, as well as areas with at least seasonally high soil moisture contents. In addition, maize and cassava are planted on the wetland fringe areas and on slopes during the dry season.

1.2.2 Sampling design of hydro(geo)logical monitoring

Figure 1.5 provides an overview of the sampling design for the hydro(geo)logical variables I monitored in the course of this study and which are described in the following chapters. The locations were selected to represent major types of land use and land cover (LULC), morphology and biophysical characteristics including soil type and hydrological regime.

Monitoring of stream discharge

Discharge of Tegu Stream was captured daily at two V-notch weirs located in the mid and lower section of the valley (Figure B.4).

Monitoring of groundwater level

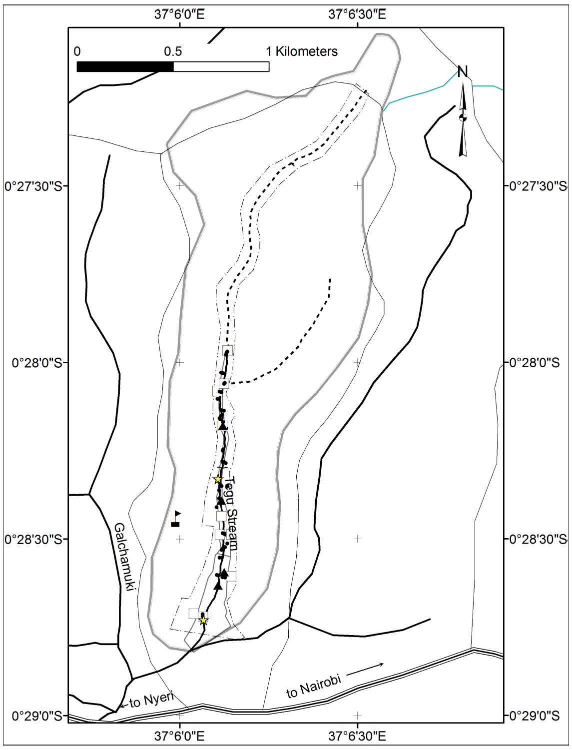
The distance between the groundwater table and soil surface was measured using piezometers. Plastic casings ("pipes") with an inner diameter of approximately 2 cm were installed inside a borehole approximately 7 cm in diameter (Figure B.1). The 2-meter-long pipes were perforated at the lower tip over a length of 30 cm to permit inflow. The holes of this screen had a diameter of about 5 mm and were covered with a bandage to prevent clogging. Gravel was placed around the screen and the remaining space between the borehole wall and the pipe above the screen to the surface was filled with manually compacted clayey soil material. The depth of the groundwater table was measured every two days.

Soil moisture monitoring

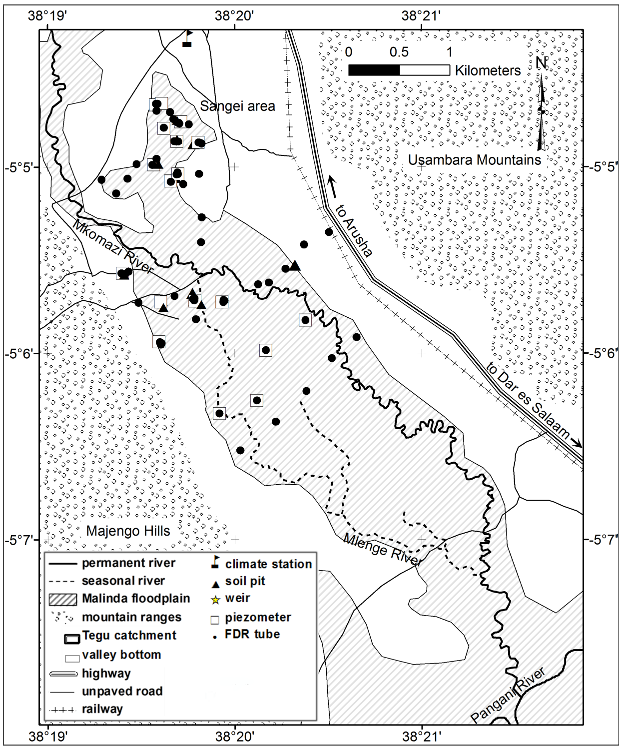
A portable Frequency Domain Reflectometry sensor, type Profile Probe PR2 (Delta-T Devices Ltd) was chosen (Figure B.2(a)). It captures volumetric soil moisture content at a depth of 10, 20, 30 and 40 cm below the soil surface. I used the Profile Probe within thin-wall fiberglass/epoxy access tubes at a length of 554 mm and a diameter of 28 mm. They maximise the penetration of the electromagnetic field into the surrounding soil (Delta-T Devices Ltd, 2008). The tubes were inserted vertically with about 50 mm remaining above ground so that they were well in contact with the soil (Delta-T Devices Ltd, 2005a).

As measurement is only possible under non-flooded conditions, the depth of ponded water was recorded during periods of flooding. Basically, the profile probe detects volumetric soil moisture θ by responding to the refractive index of the damp soil which is $\sim$ equivalent to $\sqrt{\epsilon}$. ϵ is the dielectric permittivity. A site-specific sensor calibration was applied to derive the equation for the conversion of probe millivolt output into volumetric soil moisture content (Chapter 3). Determining θ is affected by electrical conductivity, temperature, soil type, clay content, organic matter content, bulk density and ion concentration (Delta-T Devices Ltd, 2008). Detailed information on the underlying principles of soil moisture monitoring with Frequency Domain Reflectometry (FDR) and the procedure of sensor calibration is provided in Chapter 3.

Measurements of soil moisture were conducted every second day in the morning prior to the sun reaching its zenith. A Moisture Meter, type HH2 by Delta-T Devices Ltd (Delta-T Devices Ltd, 2005b), was used for the reading. During the monitoring period, information on land use and type of ground cover, cultivated crop and crop development was recorded.



(a)



(b)

Figure 1.5: Sampling design for monitoring of hydrometeorological variables: (a) Tegu inland valley, Kenya; (b) Malinda floodplain, Tanzania. Catchment area of Malinda floodplain not displayed.

1.2.3 Infiltration rates and saturated hydraulic conductivity

The saturated hydraulic conductivity K_s was measured for the upper soil layers using a Compact Constant Head Permeameter (Eijkelkamp Agrisearch Equipment) at the floodplain site (Figure B.2(b)).

This device is able to provide up to -200 cm of water pressure and can therefore operate in an auger hole down to approximately 200 cm below the device. The retrieved data for K_s is representative of the soil around the wetted perimeter of the auger hole. An auger with a 6-cm-long cutting head was applied as recommended by the manufacturer. The device does not permit to specifically determine K_s of thin soil layers (e.g. 10 cm depth). In most cases, the auger hole was watered prior to measurement to reduce the time required for reaching saturated conditions. I assumed that steady-state conditions were reached when the rates for three consecutive measurements were equal. The Glover solution was used for calculating K_s (Amoozegar, 1989).

The double-ring method was applied to measure the infiltration rate of the topsoil (Normenausschuss Wasserwesen im DIN, 2007) (Figure B.3). The saturated hydraulic conductivity can be derived from the infiltration rate. I used a pair of stainless steel infiltration rings with the diameters 28/53 cm and a height of 25 cm. The outer ring limits the lateral spread of water after infiltration (as this applies in particular for heterogeneous soils).

I watered the sites prior to installation to avoid the impact of unsaturated soil portions and to reach the state of saturation faster. Cracking of the soil was a serious problem at some sites (Figure B.3(b)).

1.2.4 Meteorological variables

The precipitation was measured with a Hellmann rain gauge which has a standardized collection area of 200 cm^2. Rainfall was captured at 1.0 m above the ground (WMO, 2008) and read once daily, at 9 a.m. (Figure B.5).

A data logger for relative humidity *r.H.* and temperature (TGU-4500 Tinytag Ultra 2 Internal Temp/RH, Gemini, 2014) was installed in a self-made wooden shelter in the style of a Stevenson Screen. The average relative humidity and the temperature for every half hour were derived based on the records. Data gaps in the time series due to data downloading, the device relaunching or temporal malfunctioning were filled using the averages from the previous and following days, where appropriate.

Starting in September 2010 in Tegu, and January 2011 in Malinda, fully automatic weather stations type “enviLog Maxi” (ecoTech, Bonn, Germany) provided measurements for the following factors at a ten-minute time step: solar radiation, air temperature and relative humidity, wind speed and direction, rainfall, air pressure and soil temperature.

During the remaining period of the project, measurements were taken using the devices described above, unless otherwise indicated in the following chapters.

I cross-validated the humidity and air temperature data of the Tinytag datalogger using the climate station. For the common measurement period, the temperature deviation was less than 3° C in about 99% of the half-hourly means. The deviation of the relative humidity was less than 10% in 97% of the cases for the Kenyan inland valley. For the Tanzanian floodplain, about 95% of the cases had deviations of less than 10%. Air humidity data provided by the climate stations at both sites were smaller than those measured by the data logger. This relationship was also valid for the temperature measurements in the inland valley. However, the opposite was the case for the floodplain.

1.3 Outline of the thesis

This thesis comprises six chapters. Chapter 1 gives an overview of the distribution of wetlands in East Africa. The reader is introduced to various concepts of wetland classification and their applications in the region. Common uses of floodplain and inland valley wetlands are outlined with a focus on their agricultural potential and use. Additionally, this chapter presents the two study sites, as well as the general materials and methods used.

The present study on soil water availability was preceded by a classification and characterisation of small wetlands in East Africa conducted by the team of the SWEA-project (Agricultural use and vulnerability of small wetlands in East Africa). The abstract of the completed paper published on this topic is part of Chapter 2. Based on the outcomes of the research, the two wetland sites were selected for the in-depth studies.

A portable Frequency Domain Reflectometry (FDR) probe was used to monitor the soil moisture contents at both study sites. Chapter 3 describes the sensor calibration procedure for wetland soils and the application of the calibration equation to a time series of profile probe readings over a period of one year in the inland valley wetland in the humid zone of Kenya.

A land use map and a digital elevation model of the Tegu valley bottom were created to relate variations in soil moisture to prevailing land use types and valley morphology. Chapter 4 depicts the findings of this multi-method approach.

Chapter 5 addresses the evaluation of soil moisture-related crop production potential in a floodplain wetland in the sub-humid zone of Tanzania. I applied the HYDRUS-1D software package to simulate the hydrological relationship between climate conditions and seasonal soil water storage, thereby closing data gaps in the time series of volumetric soil moisture contents. With this information, I calculated the length of growing period (LGP) for different land use types and landscape positions within the floodplain wetland.

Chapter 6 provides a general discussion of the results described in the previous chapters and draws conclusions based on the findings.

Chapter 2

Classification, characterisation, and use of small wetlands in East Africa

This chapter has been published under: Sakané, N., Alvarez, M., Becker, M., Böhme, B., Handa, C., Kamiri, H., Langensiepen, M., Menz, G., Misana, S., Mogha, N., Möseler, B.M., Mwita, E., Oyieke, H., van Wijk, M.T.: Classification, Characterisation, and Use of Small Wetlands in East Africa, Wetlands, 31, 1103-1116, doi: 10.1007/s13157-011-0221-4, 2011.

2.1 Abstract

Small wetlands in Kenya and Tanzania cover about 12 million ha and are increasingly converted for agricultural production. There is a need to provide guidelines for their future protection or use, requiring their systematic classification and characterisation. Fifty-one wetlands were inventoried in 2008 in four contrasting sites, covering a surveyed total area of 484 km^2. Each wetland was subdivided into sub-units of 0.5-458 ha based on the predominant land use. The biophysical and socio-economic attributes of the resulting 157 wetland sub-units were determined. The wetland sub-units were categorized using multivariate analyses into five major cluster groups. The main wetland categories comprised: (1) narrow permanently flooded inland valleys that are largely unused; (2) wide permanently flooded inland valleys and highlands floodplains under extensive use; (3) large inland valleys and lowland floodplains with seasonal flooding under medium use intensity; (4) completely drained wide inland valleys and highlands floodplains under intensive food crop production; and (5) narrow drained inland valleys under permanent horticultural production. The wetland types were associated with specific vegetation forms and soil attributes. Agricultural land use of wetlands was linked to their physical accessibility and the availability of adjacent upland areas, irrespective of wetland size or soil type.

Chapter 3

Calibrating a FDR sensor for soil moisture monitoring in a wetland in Central Kenya

This chapter has been published under: Böhme, B., Becker, M., Diekkrüger, B.: Calibrating a FDR sensor for soil moisture monitoring in a wetland in Central Kenya, Physics and Chemistry of the Earth, Parts A/B/C, 66, 101-111, doi: 10.1016/j.pce.2013.09.004, 2013.

Please note that in the published paper Θ_V has been used for volumetric soil moisture content. For the purpose of uniformity we use θ here instead. Gravimetric moisture content has the symbol θ_G.

3.1 Abstract

The recent transformation of wetlands into farmland in East Africa is accelerating due to growing food-demand, land shortages, and an increasing unpredictability of climatic conditions for crop production in uplands. However, the conversion of pristine wetlands into sites of production may alter hydrological attributes with negative effects on production potential. Particularly the amount and the dynamics of plant available soil moisture in the rooting zone of crops determine to a large extent the agricultural production potential of wetlands. Various methods exist to assess soil moisture dynamics with Frequency Domain Reflectometry (FDR) being among the most prominent. However, the suitability of FDR sensors for assessing plant available soil moisture has to date not been confirmed for wetland soils in the region. We monitored the seasonal and spatial dynamics of water availability for crop growth in an inland valley wetland of the Kenyan highlands using a FDR sensor which was site-specifically calibrated. Access tubes were installed within different wetland use types and hydrological situations along valley transects and soil properties affecting soil moisture (organic C, texture, and bulk density) were investigated. There was little variation in soil attributes between physical positions in the valley, and also between topsoil and subsoil attributes with the exception of organic C contents. With a root mean squared error of 0.073 m^3/m^3, the developed calibration function of the FDR sensor allows for reasonably accurate soil moisture prediction for both within-site comparisons and the monitoring of temporal soil moisture variations. Applying the calibration equation to a time series of profile probe readings over a period of one year illustrated not only the temporal variation of soil moisture, but also effects of land use.

Keywords: Inland valley, Wetland, Capacitance sensor, Calibration, Kenya, Soil moisture

3.2 Introduction

Combinations of subsistence agriculture in the uplands with the exploitation of wetland resources were a widespread and common traditional livelihood strategy for populations in many African countries (Silvius et al., 2000). Particularly in East Africa, the conversion of pristine or largely unused wetlands into cropland has been accelerated recently as a result of demographic growth, increased food requirements, and emerging upland shortages (Kangalawe and Liwenga, 2005; Mwakaje, 2009). Additional factors driving wetland uses are a declining crop production potential on frequently degraded upland soils, and an increasing unpredictability of precipitation, but also recent technical innovations, the emerging commercialization of production and value chains, and government policies (Maitima et al., 2009; Thornton et al., 2010; Wood and van Halsema, 2008). In the foreseeable future wetlands will become the "new agricultural frontier" or the potential "food basket" of the region.

This prognosis is based on the one hand on the relatively large available wetland areas, reaching 2.5 and 7.0% of the land surface of Kenya and Tanzania, respectively (Bakobi, 1993; Njuguna, 1996), and on the other hand on the availability of water, even during the dry season, and often favourable soil conditions for crop productions, including high organic matter content, neutral pH values and relatively large soil nutrient stocks (Wood and van Halsema, 2008).

However, wetlands are not only potential sites for current and future agricultural production, they are also providers for a variety of ecosystem services, including water provisioning (Kangalawe and Liwenga, 2005; Rebelo et al., 2010). Thus, the conversion of wetlands into farmland results in biophysical state changes, potentially affecting the availability and quality of water resources (Dixon and Wood, 2003; Motsumi et al., 2012), but also soil attributes (Kamiri et al., 2013a), and biodiversity (Owino and Ryan, 2007). These alterations are likely to negatively impact on the wetland's ability to fulfill its diverse functions and services, including eventually the agricultural production potential.

Especially the small wetlands with sizes <500 ha have received little research attention until recently (Mwita et al., 2013). This gap is being addressed by the German-East African collaborative research project "Agricultural use and vulnerability of small wetlands in East Africa" (SWEA, 2013) in selected wetland sites of Kenya and Tanzania. It seeks to provide scientifically-based arguments to support a sustainable use of small wetlands in East Africa while minimizing negative environmental impacts.

The present study aims to assess the potential impact of land use and climate change on the wetlands' hydrological functioning. Hydro(geo)logical studies addressing 'environmental flows' often focus on time series of river flow (Kashaigili et al., 2007; McCartney, 2000), while ecologists focus mainly on water table fluctuations to explain changes in plant species composition of wetlands (Hájek et al., 2013). However, it is the amount and the dynamics of plant available soil moisture in the rooting zone of crops that determine to a large extent the agricultural production potential of wetlands and thus require increased research attention in the face of wetland conversion into sites of production.

Several methods are available for this moisture monitoring. The gravimetric method has been applied for a long time and in a wide range of studies (Reynolds, 1970). Yet, the method is time and labour consuming and hardly permits soil moisture monitoring at the same spot due to its destructive character. This is particularly disadvantageous at sites with large spatial heterogeneity and temporal variability in soil properties (Bruland and Richardson, 2005).

Since the 1950s, neutron probes became widely available and were extensively used during the 1970s and 1980s (International Atomic Energy Agency, 2008). While their high level of accuracy has been confirmed (Evett et al., 2012, 2009), their broad field-scale application is limited by security and health regulations.

Electromagnetic sensors (EM sensors) which respond to changes in the soil bulk electrical permittivity (ϵ) became commercially available in the 1980s. Today, Time Domain Reflectometry (TDR), quasi-TDR systems, and Frequency Domain Reflectometry (FDR) systems are most commonly applied for monitoring of soil moisture content. A fast rise step voltage pulse propagates as electromagnetic wave into the soil guided by the conductors of the TDR probe (Topp and Reynolds, 1998). The travel time of the wave is related to the dielectric constant of the soil. An empirical equation is required to link relative permittivity to volumetric soil moisture content.

FDR sensors (capacitance sensors) use the interaction of the fringing field of the capacitance sensor with the surrounding soil, whereby the capacitance is influenced by the soil bulk electrical permittivity and thus by soil moisture content (International Atomic Energy Agency, 2008). The frequency of oscillation decreases with increasing moisture contents. The frequency of oscillation is also affected by the content of clay minerals and by temperature (Evett et al., 2006; Hanson and Peters, 2000).

Thus, depending on the required accuracy and the prevailing field conditions, site-specific calibration is required (Bullied et al., 2007; Doležal et al., 2008). Wetland soils are a particular challenge for the application of these systems because of their high moisture contents and often high contents of clay and organic matter, but frequently also high salinity which may interfere with FDR measurements.

While reliable calibrations for EM sensors are available for most upland soils (Jacobsen and Schjønning, 1993; Little et al., 1998), no such data data exist to our knowledge for tropical wetland soils. To fill this gap, we tested the suitability of a capacitance sensor system for soil moisture monitoring in an inland valley wetland in the humid zone of Kenya. We evaluated the requirements for a soil-specific calibration to derive suitable estimates of water content and availability of the valley bottom soils. In view of developing a unified calibration equation, data on land use, soil texture and soil organic carbon content, but also of landscape position (e.g. central part, fringe, and downslope of the valley bottom land) were collected and used in clustering sites and wetland segments with common attributes.

Our objectives were to: (i) understand the site specific variability of soil properties which might affect the response of the EM sensor and its calibration; (ii) calibrate an EM sensor in the field and validate the accuracy of calibrations; and (iii) describe exemplarily temporal dynamics of soil moisture contents for the study wetland.

3.3 Materials and methods

3.3.1 Study area

The study area is located south of Mount Kenya, Central Province of Kenya, between latitudes 0°27’11"-0°28’49"S and longitudes 37°5’53"-37°6’36"E (Figure 3.1). The inland valley of Tegu Stream lies at 1720-1800 m altitude in the upper reaches of Tana River, the largest river in Kenya, which flows over nearly 1000 km from Mount Kenya and the Aberdare Mountains to the Indian Ocean (Leauthaud et al., 2012).

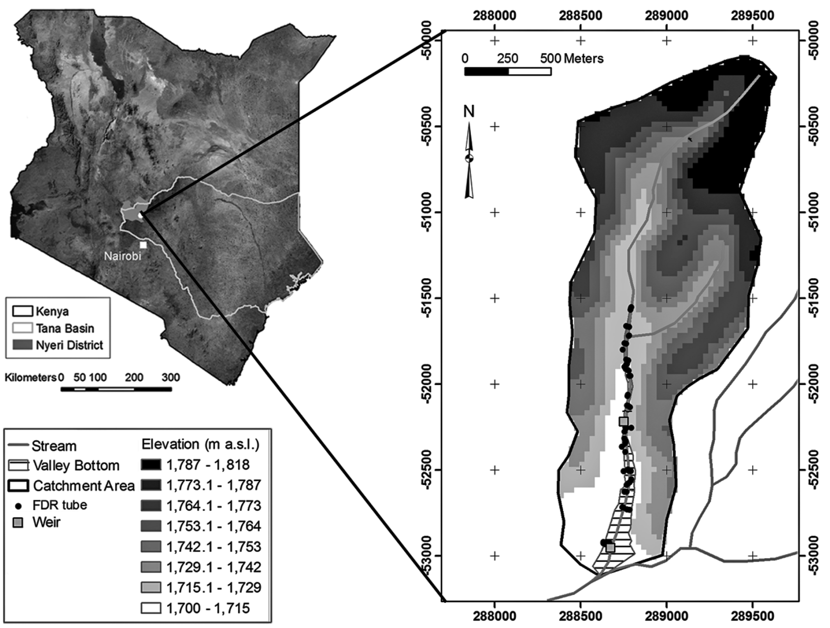


Figure 3.1: Location and topography of the inland valley in Kenya, Nyeri district (Kenya map data from Map Library (2013), elevation data from ASTER (NASA, 2009)).

The Tegu site was selected as being representative for wetlands in the humid highlands based on a comprehensive characterization of agriculturally used wetlands in East Africa (Sakané et al., 2011). The catchment area of the wetland covers 2.4 km^2 with about 9 ha of valley bottom land extending in North-South direction over a distance of 1.5 km and with a width of 15-200 m. Slopes range from 5% to 36% inclination.

Applying the morphological approach of inland valley classification suggested by Windmeijer and Andriesse (1993), the study area is assigned to the type “stream inland valley” and includes the valley head and the midstream section.

The area belongs to the main coffee-growing zone UM2 (Jaetzold et al., 2006) with a length of growing period of 270 days (Kamiri, 2010). Annual rainfall of about 1450 mm (Karatina Agricultural Office) occurs in a bimodal pattern, with long rains between March and June, and short rains between October and December (van der Sombroek et al., 1982). Mean annual temperature is about 16.5° C. While the water flow in the central river bed is permanent, it is substantially reduced by water abstraction for irrigation during the dry season. Water flow in the upstream valley head is seasonal.

Upland soils developed on volcanic material. They are classified as Nitisols (FAO, 2006). Along the valley slopes an impermeable layer of saprolyte occurs at 25-60 cm below the surface (Kamiri, 2010). A very deep and poorly drained Dystric Fluvisol is the dominant soil type in the valley bottom (Njoroge and Macharia, 2009).

The valley bottom is still partially under natural vegetation (mainly *Cyperus* spp.) but is increasingly converted for the cultivation of food crops (mainly *Zea mays* and *Colocasia esculenta*). Arrowroot (*C. esculenta*) is a tuber crop widely distributed in the tropics and subtropics. In the study area, it is cultivated under flooded conditions; though it can be also grown under upland conditions (Onwueme and Charles, 1994). The labour intensive land preparation, such as clearing, ploughing, and puddling, is mostly done by women.

The production of maize in the valley bottom is constrained by excess moisture due to the high water tables (Zaidi et al., 2012). Therefore maize plots are located at slightly raised beds. A network of small canals allows for plot drainage during the rainy season and for supplementary irrigation during the dry season. During periods of waterlogging, parts of the valley are left fallow. The slopes are cultivated with coffee and diverse food crops, intercropped with napier grass (*Pennisetum purpureum*) and both exotic (*Graveria* spp., *Eucalyptus* spp.) and native (*Prunus africana*) tree species.

3.3.2 Sampling design of soil moisture monitoring

Over a period of 21 months (2009-2011), 52 locations within Tegu wetland were monitored for seasonal soil moisture content, covering the diversity of prevailing land uses (unused/fallow, pasture, upland crops, flood-tolerant crops/arrowroot) and geomorphological characteristics (Table 3.1).

Table 3.1: Number of sites for soil moisture monitoring and calibration of Frequency Domain Reflectometry (FDR) sensor along and across the Tegu valley, Kenya. M = site used for moisture monitoring, C = site used for calibration of sensor.

		Cross-section					
Longitudinal	**Land use type /**	Central		Fringe		Lower slope	
section	**major crop**	M	C	M	C	M	C
Upper	Arrowroot (AR)	6	6	7	7	-	-
	Fallow (FA)	2	2	2	2	-	-
	Upland crops (UP)	2	2	4	4	-	-
	Pasture (PA)	-	-	-	-	-	-
	Slope	-	-	-	-	2	-
Mid	Arrowroot (AR)	4	4	5	4	-	-
	Fallow (FA)	2	1	-	-	-	-
	Upland crops (UP)	3	3	1	1	-	-
	Pasture (PA)	-	-	2	2	-	-
	Slope	-	-	-	-	3	-
Lower	Arrowroot (AR)	3	2	4	4	-	-
	Fallow (FA)	-	-	-	-	-	-
	Upland crops (UP)	2	2	3	3	-	-
	Pasture (PA)	-	-	-	-	-	-
	Slope	-	-	-	-	-	-

The longitudinal extent of the valley was subdivided into upper, mid, and lower section while the cross-section of the valley (toposequence) was subdivided into central valley bottom (poorly drained), valley bottom fringe (seasonally wet) and lower valley slope (well drained). Each of these positions was equipped with at least two access tubes for FDR measurements.

Only few pasture areas are located in the upper and lower section of Tegu valley. Therefore, no monitoring sites were established there. Lower slope sites were not equipped with FDR tubes in the lower section as well, and land use at the lower slope sites was not differentiated in this part of the study.

As the perched water table in the valley bottom never receded below 50 cm, moisture measurements were conducted at 10, 20, 30, and 40 cm below the soil surface every two days. Stream discharge was captured daily at two V-notch weirs located in the mid and lower section of the valley. Daily precipitation was measured with a Hellmann rain gauge according to WMO standard (WMO, 2008).

3.3.3 Laboratory analyses

Soil texture at 10, 20, 30 and 40 cm below soil surface was analyzed using the pipette method (Table 3.2). Organic matter was destroyed with hydrogen peroxide prior to analysis. Content in organic carbon for the same depths was measured by a modified Walkley-Black wet digestion (Anderson and Ingram, 1993). Bulk density was determined with the core method using the same samples as for calibration of the profile probe. Moisture retention curves for the top 40 cm of four distinct soil profiles (described in Njoroge and Macharia, 2009) were determined in pressure chambers with ceramic plates (Hinga et al., 1980).

Table 3.2: Location of sampling sites for organic C along (upper, mid, lower section) and across (central, fringe) the Tegu valley. Land use types/major crop provided in Table 3.1.

Land use type/	**Upper section**		**Mid section**		**Lower section**	
major crop	Central	Fringe	Central	Fringe	Central	Fringe
AR	3	3	1	1	2	-
FA	1	1	-	-	2	-
UP	1	3	-	-	-	-
PA	-	-	-	1	-	-

3.3.4 Calibration of capacitance system with volumetric moisture content samples

We opted for the capacitance system PR2 by Delta Devices Ltd., Cambridge, UK, for soil moisture monitoring (Delta-T Devices Ltd, 2008). It is designed to make portable readings from within an access tube simultaneously at four depths down to 40 cm. Three sensor readings were taken in each depth with the probe rotated 120° between readings. The profile probe consists of a sealed polycarbonate rod of 25 mm diameter, with electronic sensors arranged at fixed intervals along its length (Delta-T Devices Ltd, 2008). The probe creates a 100 MHz signal which is transmitted as an electromagnetic field extending about 100 mm into the soil.

The volumetric soil moisture θ can be predicted from the square root of the soil bulk electrical permittivity ϵ using the following equation (Delta-T Devices Ltd, 2008).

$$\sqrt{\epsilon} = a_0 + a_1 \times \theta \tag{3.1}$$

whereby a_0 is the soil offset and a_1 the slope. For generalised mineral (min) soils and organic (org) soils, a_0 and a_1 are provided by manufacturer (a_0(min)=1.6, a_0(org)=1.3, a_1(min)=8.4, a_1(org)=7.7).

The manufacturer's calibrations for the profile probe are optimised for mineral soils with organic carbon contents of $\sim$ 1% and bulk densities >1 g/cm^3 and for organic soils with contents of organic C of $\sim$ 40% and bulk densities <1 g/cm^3 (Delta-T Devices Ltd, 2008). The relationship between the volt output V of the PR2 and $\sqrt{\epsilon}$ is fitted by a polynomial equation (Equation 3.2) up to moisture contents of $\sim$ 0.5 m^3/m^3:

$$\sqrt{\epsilon} = 1.125 - 5.53 \times V + 67.17 \times V^2 - 234.42 \times V^3 + 413.56 \times V^4 - 356.68 \times V^5 + 121.53 \times V^6 \tag{3.2}$$

Combining Equations 3.1 and 3.2 results in a polynomial conversion (Equation 3.3) for volumetric soil moisture contents θ [m^3/m^3]: where a_0 and a_1 are the calibration coefficients from Equation 3.1.

$$\theta = \frac{(1.125 - 5.53 \times V + 67.17 \times V^2 - 234.42 \times V^3 + 413.56 \times V^4 - 356.68 \times V^5 + 121.53 \times V^6 - a_0)}{a_1} \tag{3.3}$$

Sample collection for calibration was conducted at two dates during the wet season (campaign 1 and 3) and at one date during the dry season (campaign 2) to represent a wide range of soil moisture conditions. Undisturbed soil samples (100 cm^3) were collected at 10-20 cm distance from the access tube at 10, 20, 30, and 40 cm below soil surface to represent soil conditions at the tube site, while minimizing soil disturbances within the electromagnetic sensor field. Samples were oven-dried at 105° C for minimum 24 h to determine gravimetric moisture content θ_G [g/g] and bulk density ρ_S [g/cm^3]. Gravimetric moisture content θ_G was converted to volumetric moisture content θ using bulk density (Equation 3.4) and results were related to *in-situ* PR2 volt output V to develop the calibration function with site-specific coefficients a_1 and a_0:

$$\theta_G = \theta \times \frac{\rho_W}{\rho_S} \tag{3.4}$$

ρ_W is the density of water [g/cm^3], ρ_S is the bulk density of soil [g/cm^3].

The PR2 does not measure temperature and bulk electrical conductivity. Furthermore, salinity levels in the study area never exceeded 10 mS/m and annual soil temperature variation was less than 10 K. Therefore these factors were not considered as variables for the calibration of the profile probe.

3.3.5 Data analyses

Variability of bulk density, texture and soil organic carbon content was evaluated using standard descriptive statistics and tests. Calibration of moisture content θ vs. sensor readings (expressed as voltage and square root of soil bulk electrical permittivity) was calculated by regression analysis. All statistical analyses were done using SPSS V.17.0. ROSETTA computer program was used to estimate soil hydraulic parameters with hierarchical pedotransfer functions (Schaap et al., 2001). Root mean squared difference (*RMSD*) between θ from gravimetric method and θ determined by PR2 using factory calibration was calculated to evaluate the accuracy of the factory calibration. Root mean squared errors (*RMSE*) of regression values were calculated as an indicator of calibration accuracy (Evett et al., 2006).

3.4 Results

With the objective of providing a reliable calibration of EM-based moisture readings for wetland soils, the following paragraphs present first the prevailing spatial (both horizontal and vertical) and temporal variation of soil attributes potentially affecting the calibration process in an inland valley wetland of Kenya (Section 3.4.1) before establishing the calibration procedure (Section 3.4.2) and its validation and use for pattern detection (Section 3.4.3).

3.4.1 Site specific variability of soil properties

We tested the variability of soil texture at 10 cm depth increments for the valley bottom using a paired-samples t-test. The assumption of normality has not been violated (Shapiro-Wilks test, α=0.05, p>0.05). The t-test failed to reveal a statistically significant difference of the mean shares of clay, silt and sand between the four depths. Mean clay contents ranged from 54% to 79%, silt contents from 18% to 40% and sand contents from 3% to 6%. A one-way ANOVA applied on the whole dataset did not reveal a statistically significant difference in the shares between the different soil depths (e.g. for clay F(3, 71)=0.271, p=0.885).

The spatial variability of texture by the position of the sampling site (fringe or central part of valley bottom, lower valley slope) yielded no clear trends, possibly due to the small sample size. The majority of samples lie within the clay-class according to USDA system.

The pairwise analysis of organic carbon contents for the four soil depth increments revealed statistically significant differences between the mean contents at 10, 20, 30 and the content at 40 cm (Figure 3.2, Table 3.3). While organic C at 40 cm depth was generally lower than at 10, 20, and 30 cm, this was not the case for three individual sites with specific land uses such as (1) pasture, (2) mulched *C. esculenta*, and (3) waterlogged fallow plots.

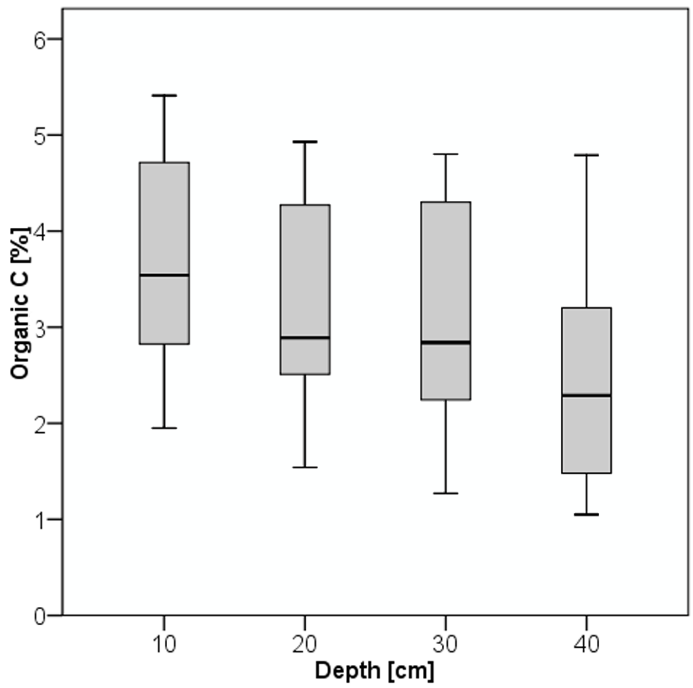


Figure 3.2: Box-and-Whisker plot of content of organic C for 10 cm increment soil samples from the inland valley in Kenya. Sample size n=19.

A one-way ANOVA applied on organic carbon contents from all sampled valley bottom sites revealed a statistically significant difference between the four depths $F(3, 72)=3.178$, $p=0.029$ (normal distribution implied by Shapiro-Wilks test). Using Tukey *post-hoc* analysis, we confirmed a statistically significant decrease by 1.1% from 10 cm (3.7±1.0%) to 40 cm (2.5±1.2%) (95% confidence interval 0.15-2.1%, $p=0.017$).

Table 3.3: Paired-samples t-test applied on mean content of organic C. Inland valley, Kenya. Bold numbers designate statistically significant difference in organic C contents at 5% level. t=t-value, df=degrees of freedom, nd=normal distribution with p-value of Shapiro-Wilks test.

Depth cm	**Mean** %	**Standard deviation** %	**Sample size**	***t(df)***	***p*-value**	**nd**
10	3.66	1.03	19	$t(18)=2.632$	0.017	0.607
20	3.24	1.10				
10	3.66	1.03	19	$t(18)=3.135$	**0.006**	0.756
30	3.03	1.25				
10	3.66	1.03	19	$t(18)=5.056$	<**0.0005**	0.225
40	2.53	1.20				
20	3.24	1.10	19	$t(18)=1.907$	0.073	0.006
30	3.03	1.25				
20	3.24	1.10	19	$t(18)=5.659$	<**0.0005**	0.114
40	2.53	1.20				
30	3.03	1.25	19	$t(18)=3.426$	**0.003***	<0.0005
40	2.53	1.20				

*In case of violation of normal distribution assumption significance of difference was confirmed with Wilcoxon signed-rank test.

The precision of determination of bulk density, expressed as coefficient of variation among the three replicates sampled at each depth, was high with a $CV<0.1$, permitting the application of the average of the three values for further statistical analysis. For sites where bulk density was sampled more than once over time, pair-wise comparisons allowed detecting temporal variations in bulk density. Only for the 40 cm depth, a difference of 0.037 g/cm^3 between October 2009 and April 2011 was statistically significant different from zero. Similar low variations of bulk density were observed for the depth-integrated comparison. The bulk density at 10, 20 and 30 cm differed significantly from that at 40 cm (paired-samples t-test, $\alpha=0.05$, $p<0.05$). Yet, again, the average difference was only 0.03-0.04 g/cm^3 and standard deviation of the difference was relatively high with 0.1 g/cm^3. This difference is in the order of the measurement error. Thus, we concluded that bulk density in our study area is time- and depth-independent.

Generally, most bulk densities are around 1.0 g/cm^3. A Spearman's rank-order correlation applied on the dataset of April 2011 (highest sample size n) showed a strong negative correlation between total pore volume and gravimetric moisture content ($r_s(162)$ =-0.856, p<0.0005).

3.4.2 Sensor calibration

From 52 access tubes providing data readings throughout the study period, three tubes had to be discarded from calibration due to permanent flooding and/or technical problems (Table 3.4). Slope sites were excluded as well.

Table 3.4: Number of sites with FDR access tubes included in three calibration campaigns of profile probe in the inland valley, Kenya. Land use types/major crop are provided in Table 3.1.

Depth cm	**Land use type / major crop**	10/2009	08/2010	04/2011	10/2009+ 08/2010	08/2010+ 04/2011	10/2009+ 04/2011	10/2009+ 08/2010+ 04/2011
10	AR	21	10	24	6	10	18	6
	FA	4	3	4	2	3	3	2
	PA	2	-	1	-	-	1	-
	UP	12	10	11	7	9	8	6
20	AR	22	5	24	2	5	19	2
	FA	4	1	4	-	1	3	-
	PA	2	-	1	-	-	1	-
	UP	11	8	11	5	7	8	4
30	AR	21	6	23	2	6	17	2
	FA	4	1	3	-	1	2	-
	PA	2	-	1	-	-	1	-
	UP	11	5	11	2	5	8	2
40	AR	20	5	22	2	5	16	2
	FA	3	1	3	-	1	2	-
	PA	2	-	1	-	-	1	-
	UP	11	4	11	1	4	8	-

The precision of determination of θ was very good with a CV<0.2 for both gravimetric and FDR-based moisture measurements for the three replicates of each sample.

The variation of θ over the monitoring period of two years exceeded 10 vol% for most sampling locations, thus complying with the prerequisite for the field calibration of the moisture probe according to manufacturer's recommendations (Delta-T Devices Ltd, 2008).

After confirming the normality of data distribution (Shapiro-Wilk test with p=0.295, α=0.05), a paired-samples t-test revealed statistically significant differences of gravimetrically sampled moisture contents θ between the first and the second sampling date (Table 3.5). Moisture changes of about 10 vol% were observed (Figure 3.3). Changes in soil moisture differed by soil depth and were most expressed in the topsoil layer and least at 40 cm depth (data not shown). The histogram of all gravimetrically determined moisture contents θ reveals that values ranged from 0.28 to 0.76 m^3/m^3 (Figure 3.4), with 75% of the samples between 0.5 and 0.7 m^3/m^3, but are not normally distributed according to Q-Q plot and Shapiro-Wilk test.

Table 3.5: Paired-samples t-test applied on mean volumetric moisture content θ obtained gravimetrically at three sampling dates in the inland valley, Kenya. Bold numbers designate statistically significant difference in θ between sampling dates at 5% level. t=t-value, df=degrees of freedom, nd=normal distribution with p-value of Shapiro-Wilks test.

Campaign	**Mean** m^3/m^3	**Standard deviation** m^3/m^3	**Sample size**	$t(df)$	p**-value**	**nd**
1	0.507	0.095	28	$t(27)$=-7.481	<**0.0005**	0.295
2	0.605	0.064				
1	0.559	0.085	115	$t(114)$=-5.051	<**0.0005***	<0.0005
3	0.585	0.072				
2	0.601	0.063	55	$t(54)$=5.980	<**0.0005***	0.012
3	0.562	0.086				

*In case of violation of normal distribution assumption significance of difference was confirmed with Wilcoxon signed-rank test.

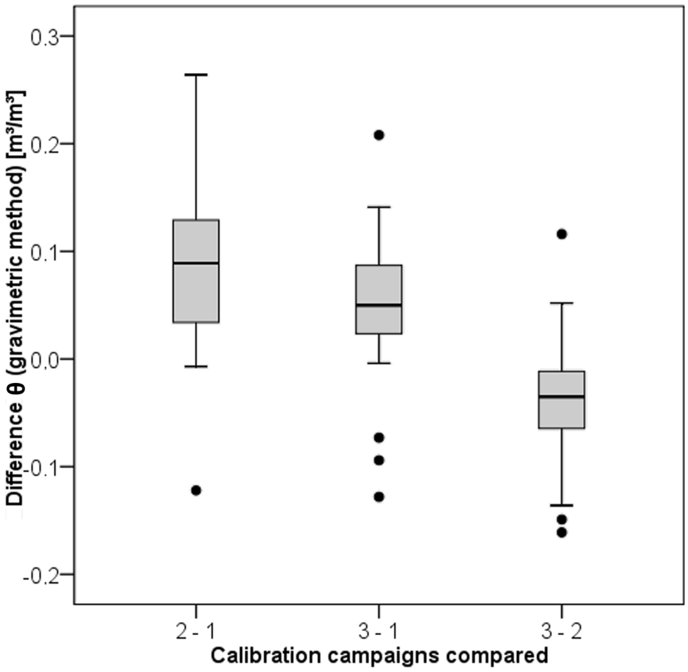


Figure 3.3: Box-and-Whisker plot of differences of volumetric moisture contents θ (gravimetric method) between the three sampling dates, October 2009 (1), August 2010 (2) and April 2011 (3). Inland valley, Kenya.

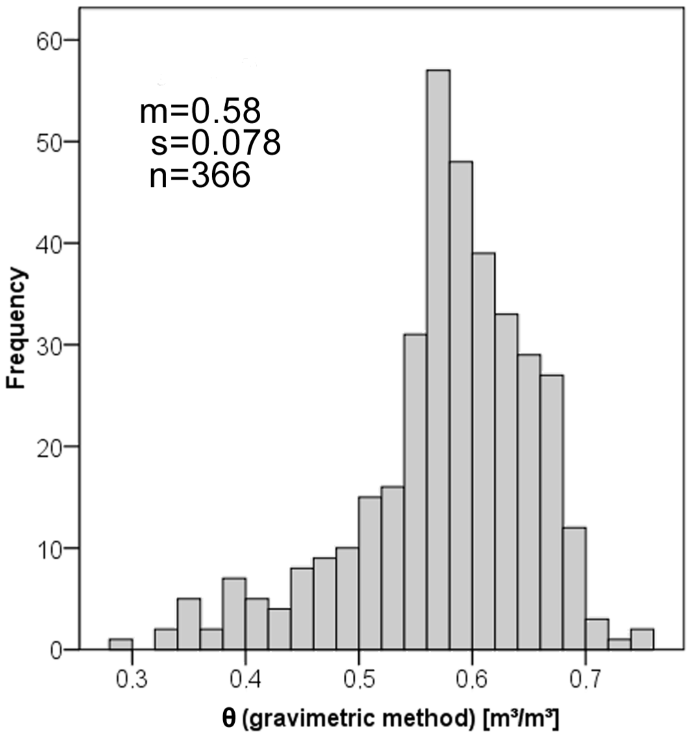


Figure 3.4: Frequency distribution of volumetric moisture contents θ (gravimetric method) from three sampling dates in the inland valley, Kenya; class size 0.02 m^3/m^3. m=mean, s=standard deviation, n=sample size.

The manufacturer's calibration function for mineral soils underestimates moisture contents in the whole measurement range by maximum 0.23 m^3/m^3 (Figure 3.5).

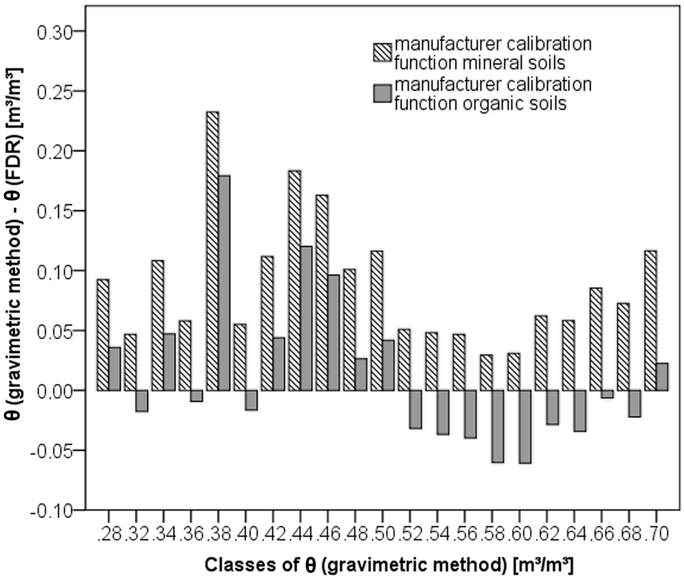


Figure 3.5: Differences between volumetric moisture contents θ (gravimetric method) and volumetric moisture contents θ (FDR) for the inland valley, Kenya. Application of manufacturer's calibration functions for mineral and organic soils. Differences averaged for classes of volumetric moisture contents θ (gravimetric method); class size 0.02 m^3/m^3.

The application of the calibration function provided for organic soils yields an underestimation of moisture contents in the dry range by 0.18 m^3/m^3 and an overestimation in the wet range by 0.06 m^3/m^3.

The average gravimetrically sampled moisture contents θ were plotted against the millivolt output mV of the profile probe (Figure 3.6). The coefficient of variation (CV) of the millivolt output of the profile probe for low moisture content classes 0.32-0.48 m^3/m^3 (mainly topsoil samples) ranged between 0.07 and 0.19 but did not show a clear trend (n=1-11). At higher moisture contents of >0.56 m^3/m^3 the millivolt output mV of the profile probe was about 980 mV with coefficients of variation <0.1 (n=6-52). This concerned mainly the samples from profile depths of 30 and 40 cm. This moisture level related to soil saturation which was determined at 0.56 and 0.76 m^3/m^3 from water retention curves in four profile pits and confirmed by estimates from ROSETTA computer program using texture classes and bulk density measurements as input parameters.

Figure 3.6 suggests that a further increase in FDR readings above 980 mV may not indicate increasing moisture levels. Thus, FDR readings >980 mV represent saturated soil conditions and lookup tables were created to link profile probe millivolt output to moisture content θ at saturation. Consequently, sensor calibration needs to focus on the value range below this saturation level and only these data were used for further analysis.

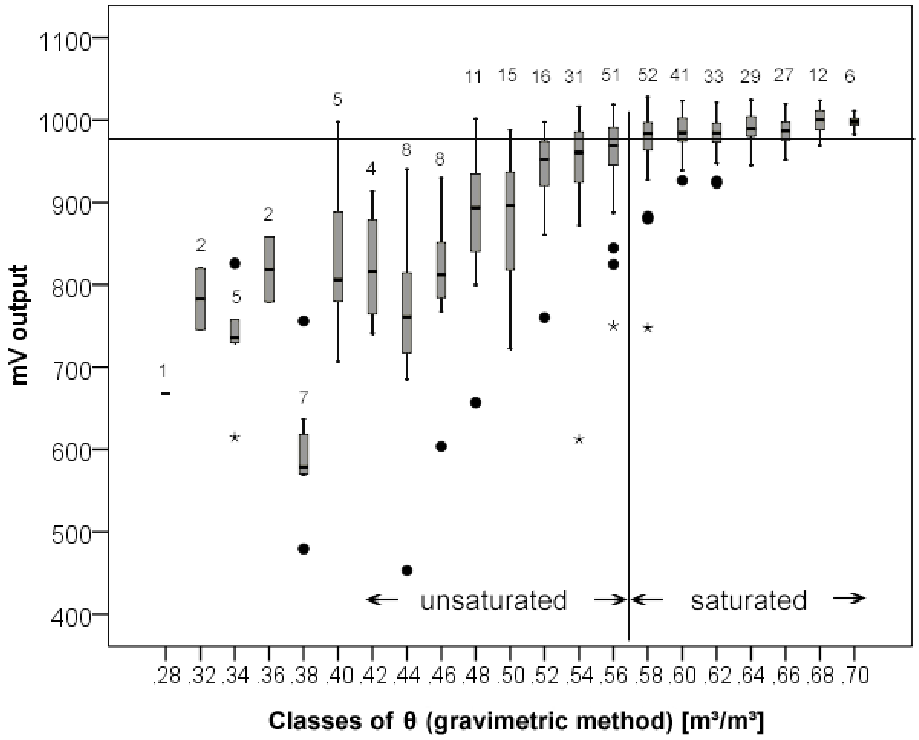


Figure 3.6: Box-and-Whisker plot of millivolt output of FDR profile probe for the inland valley, Kenya. Labels at x-axis are classes of volumetric moisture contents θ (gravimetric method); class size 0.02 m^3/m^3. Horizontal line indicates set boundary for saturated soil conditions. Number above each box indicates sample size *n*. Extreme outliers are illustrated as an asterisk (*). They are outside the outer fence of the boxplot, i.e. the first quartile minus three times the interquartile range (*IQR*), or the third quartile plus three times *IQR*.

The calibration procedure was partially hampered by the high variability of millivolt output within each moisture content class and the small sample size (Figure 3.6). We established several linear relationships between $\sqrt{\epsilon}$ (calculated from volt output V using Equation 3.2) and θ from gravimetric method [m^3/m^3] using subsets of different land uses, soil depths or combinations of both (Table 3.6).

The best goodness-of-fit (R^2>0.7) was observed for the topsoil regression equations covering all land use types. The strength of the linear relationship for the subsoil (30 and 40 cm below soil surface) was considerably smaller with R^2<0.5.

Table 3.6: Model parameters and goodness-of-fit statistics for linear relationships[a] between $\sqrt{\epsilon}$ and θ obtained gravimetrically. Inland valley, Kenya. Bold numbers designate statistically significant linear relationship at 5% level. Land use types/major crop are provided in Table 3.1.

Subset (land use type)	**Soil depth**	$\mathbf{a_1}$	$\mathbf{a_0}$	$\mathbf{R^2}$	***F***	***p*-value**
all land use types	10-40 cm	9.47	0.10	0.65	$F(1, 196)=365.70$	<**0.0005**
AR/FA	10-40 cm	10.42	-0.50	0.66	$F(1, 113)=215.82$	<**0.0005**
PA/UP	10-40 cm	8.96	0.45	0.64	$F(1, 81)=146.81$	<**0.0005**
AR/FA	10 cm	10.73	-0.76	0.73	$F(1, 45)=123.70$	<**0.0005**
PA/UP	10 cm	9.34	0.14	0.78	$F(1, 33)=115.68$	<**0.0005**
AR/FA	30+40 cm	13.80	-2.25	0.48	$F(1, 17)=15.46$	**0.001**
PA/UP	30+40 cm	7.90	1.28	0.35	$F(1, 14)=7.514$	**0.016**

[a] $\sqrt{\epsilon} = a_0 + a_1 \times \theta$

We decided to further use the calibration equation derived from the whole dataset as it promises the widest applicability.

$$\sqrt{\epsilon} = 0.103 + 9.466 \times \theta \tag{3.5}$$

However, the data set did not show homoscedasticity due to high sample number and low variance at higher moisture levels and vice versa for lower moisture levels.

Yet, as this distribution is very typical for wetland field conditions, we accepted the violation of the homoscedasticity assumption for linear regression analysis and polynomial conversion for volumetric soil moisture contents from PR2 volt output V was applied:

$$\theta = \frac{(1.125 - 5.53 \times V + 67.17 \times V^2 - 234.42 \times V^3 + 413.56 \times V^4 - 356.68 \times V^5 + 121.53 \times V^6) - 0.103}{9.466} \quad (3.6)$$

The root mean squared error ($RMSE$) of our regression values was 0.073 m^3/m^3 (Figure 3.7). The root mean squared difference ($RMSD$) as a measure of the factory calibration accuracy was 0.091 m^3/m^3 (mineral soil) and 0.085 m^3/m^3 (organic soil), respectively.

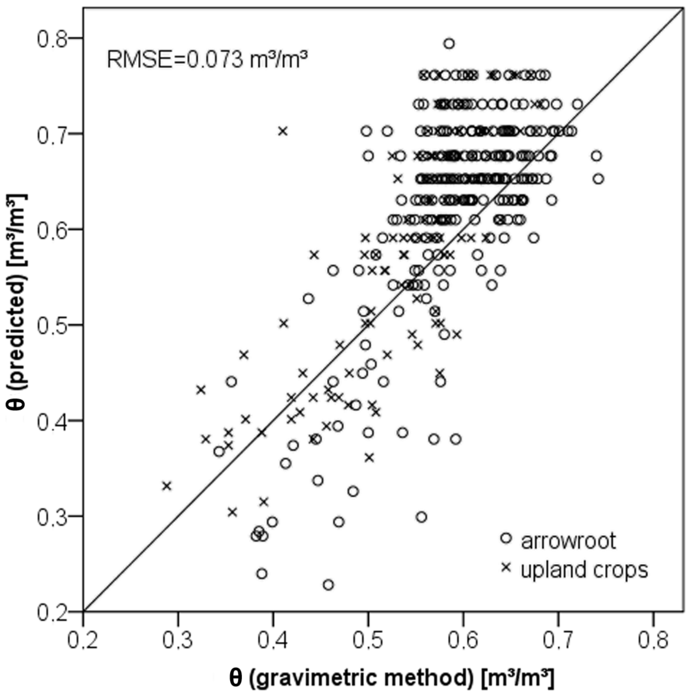


Figure 3.7: Scatter plot of FDR-based volumetric moisture contents θ predicted with new calibration function against volumetric moisture content θ (gravimetric method). Inland valley, Kenya. The solid line shows the 1:1 ratio.

3.4.3 Temporal soil moisture patterns for two land use types

The gravimetrically determined soil moisture contents from the calibration campaign in April 2011 indicated differences in moisture contents at 10, 20, and 30 cm depth depending on land use type (Figure 3.8). Thus, soil moisture significantly differed at 20 cm soil depth between arrowroot (*C. esculenta*) (0.61 ± 0.06 m^3/m^3) and upland crops (mainly *Z. mays*) cultivated on the valley bottom (0.55 ± 0.07 m^3/m^3) ($F(1, 34)=7.541$, $p=0.01$, one-way ANOVA). Though statistically not significant, the different moisture regimes mirror the land use type in the upper 30 cm soil column.

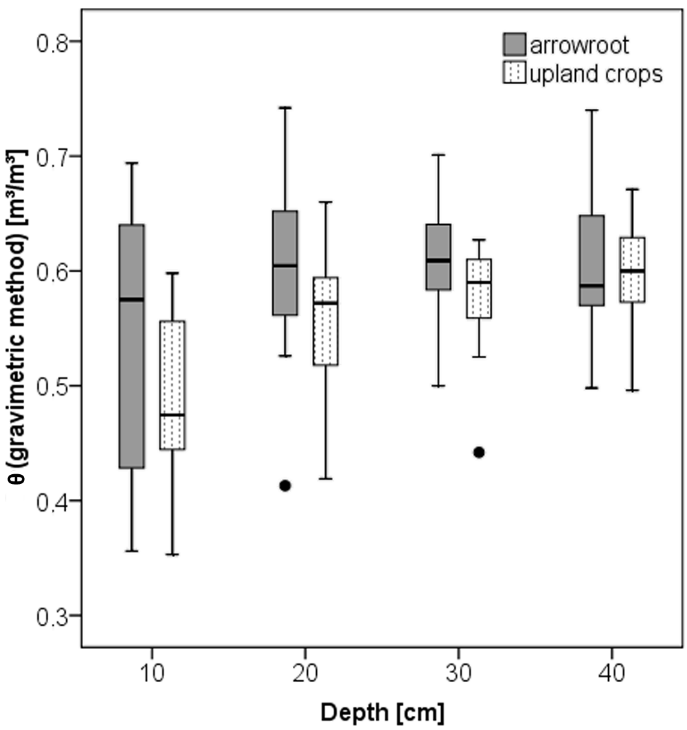


Figure 3.8: Depth-integrated volumetric soil moisture contents θ (gravimetric method) separately averaged over plots cultivated with arrowroot (*Colocasia esculenta*) and plots cultivated with upland crops (mainly maize) in the inland valley bottom, Kenya. Data from sampling campaign in April 2011.

For two selected sites, one cultivated with arrowroot, and one cultivated with maize, time series of volumetric moisture contents were plotted against daily rainfall for the year 2010 (Figure 3.9). Moisture contents at 30 cm depth were close to saturation in both plots due to the shallow groundwater table. Annual moisture variations in the topsoil of the maize plot were stronger and the relationship between moisture content and rainfall was more expressed. The moisture content was generally about 10% lower in the topsoil of the maize plot than in the plot under arrowroot and nearly reached the Permanent Wilting Point before the onset of the long rains (day 40).

The plot with arrowroot experienced mostly moisture levels above field capacity which is in line with the crops' growing requirements.

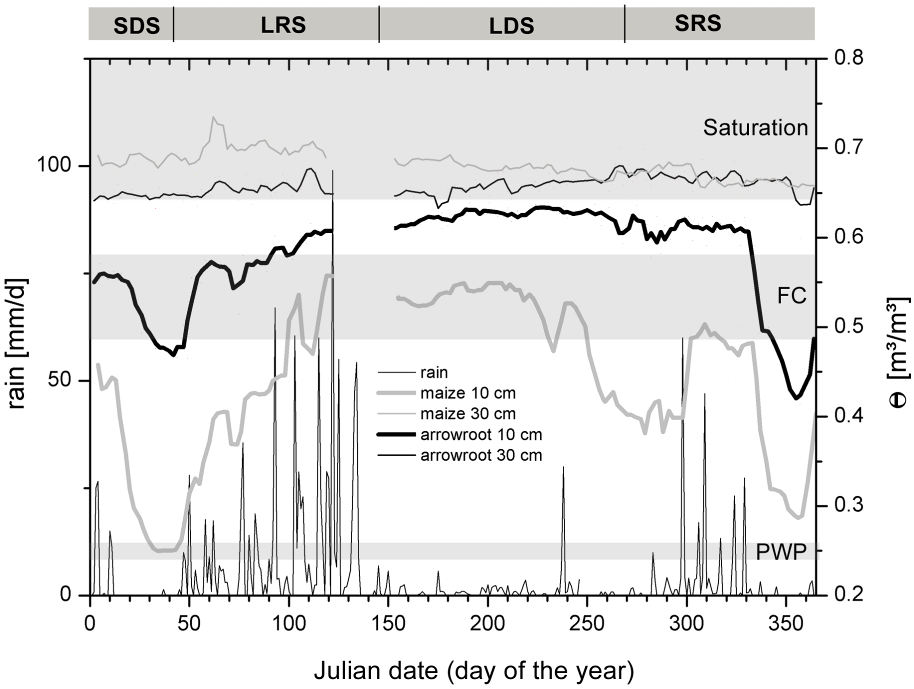


Figure 3.9: Temporal variation of FDR-based volumetric moisture contents θ in the topsoil (10 cm, thick lines) and subsoil (30 cm, thin lines) plotted against daily rainfall. Moisture contents obtained from new calibration function. Plot cultivated with maize (*Zea mays*, grey curves) vs. plot cultivated with arrowroot (*Colocasia esculenta*, black curves) in the valley bottom of Tegu wetland, Kenya. Monitoring period January to December 2010, data gap between day 120 and 160 due to flooding. Grey shaded boxes represent ranges of Permanent Wilting Point (PWP), Field Capacity (FC) and Saturation. SDS=Short Dry Season, SRS=Short Rainy Season, LDS=Long Dry Season, LRS=Long Rainy Season.

3.5 Discussion

In the present study we followed a step-wise approach to describe variations of soil moisture content and determining soil attributes in the bottom of an inland valley in Central Kenya in view of developing and validating a protocol for the calibration of an EM moisture sensor. The need for the present work arose because of insufficient data on calibrating FDR sensors for wetland conditions.
Standard calibration procedures are hampered by a range of soil attributes that are typical for many wetland soils and that can interfere with the calibration procedure. These concern large total pore volume, high clay contents, and high to very high organic C contents in these often histic Fluvi- or Gleysols (Edem and Ndaeyo, 2009). Clay contents in our study area were between 54-79%. The organic C content was 2-5% but could reach as much as 10% (Kamiri et al., 2013a) in some areas (Histosols).

The bulk density was around 1 g/cm^3 and was negatively correlated with the moisture content, reflecting the shrinking and swelling behavior of the clay soils typical for wetlands and reported also by Fares et al. (2004). These bulk density values are distinctly lower than those of the adjacent upland soils for which EM-probes have been calibrated. Finally, the soil of inland valley wetlands is for large parts of the year saturated. In the present study, this was particularly true at soil profile layers below 20 cm.

While the observed relative homogeneity of bulk density, organic C and texture across the study site is advantageous for the purpose of calibrating the FDR sensor, it may limit the potential for interpretation and extrapolation of the findings to other wetland environments.

Future studies in more variable wetlands may be needed to confirm the protocol of sensor calibration. The FDR sensors used in access tubes are a convenient and affordable method for soil moisture monitoring as they are non-destructive (unlike gravimetric samples) and allow repeated depth-integrated measurements at many sites with one sensor.

Field calibration of the capacitance sensor using the gravimetric method was an applicable way for our research question. *RMSD* for manufacturer's calibration function was 0.091 m^3/m^3 (manufacturer's calibration function for mineral soils), and 0.085 m^3/m^3 (manufacturer's calibration function for organic soils) respectively. *RMSE* as an indicator of accuracy of our calibration equation was 0.073 m^3/m^3. *RMSE* for laboratory calibration of FDR sensors for humid tropical clayey soils of volcanic origin are reported with 0.003-0.012 m^3/m^3 (Veldkamp and O'Brien, 2000).

Evett et al. (2006) reported *RMSE* of 0.026-0.029 m^3/m^3 for three soil types under laboratory conditions which is in the same order as the results of Huang et al. (2004) for field calibration of sandy loams. A study on a clay loam soil in the San Joaquin Valley of California yielded *RMSE* of 0.063 m^3/m^3 (Mazahrih et al., 2008).

Calibration accuracy of FDR sensors can be reduced by several factors. Gravimetric samples not directly from adjacent to the access tube (as for our 1^{st} and 2^{nd} calibration campaign) are problematic for field calibration due to the small volume sensed by the capacitance systems used in access tubes (Evett et al., 2002), whereby the sensed volume further decreases with increasing water content.

For our approach, we had to imply homogeneous soil moisture contents around the access tube. Geostatistical analysis (variogram modelling) would be a helpful tool to capture the spatial variability of the soil moisture distribution around the access tubes (Herbst and Diekkrüger, 2003).

The negatively skewed distribution of the gravimetrically sampled moisture contents with higher scores at moisture levels above 0.4 m^3/m^3 was a challenge for sensor calibration. However, this distribution reflects real-ground situation. Thus, the preservation of the strong weighting of high moisture levels in the linear regression analysis was justified.

It has been proven repeatedly that the frequency of oscillation of electrical signals of EM sensors is affected by bulk density, clay content, bulk electrical conductivity, and temperature (Bullied et al., 2007; Doležal et al., 2008) whereby most of the temperature dependence of capacitance probes may be due to the temperature dependence of bulk electrical conductivity (Baumhardt et al., 2000). Out of these factors we studied bulk density and clay content which were rather uniform across the study area. Soil water salinity (10 mS/m) and annual temperature variations ($<$10 K for slope site) were much lower than levels reported as sensitive for laboratory calibration (Baumhardt et al., 2000). Inclusion of these factors could potentially improve accuracy of the calibration equation, yet other undetermined factors might also affect the electric properties of the soil (Jacobsen and Schjønning, 1993).

Considering these limitations for our calibration procedure, the accuracy of the calibration function is acceptable for describing the relative temporal soil moisture variations and for within-area comparisons.

We demonstrated exemplarily the application of the derived calibration function for prediction of EM-based moisture contents at two selected sites. While near-permanent topsoil saturation was observed in the case of arrowroot (*C. esculenta*) cultivation, there was at least seasonal topsoil drying nearly reaching Permanent Wilting Point under maize (*Z. mays*). Already at 30 cm below the soil surface, saturated conditions were observed. This bears the risk of anaerobic stress for growth of maize crops.

Water content governs the aeration status of the soils, depending on soil texture and related soil pore system. Fine textured wetland soils under prevailing (near-to) saturated conditions entail anaerobic conditions where organic carbon can accumulate, promoted by high productivity of these ecosystems (Mitsch and Gosselink, 2000). The positive correlation between cation exchange capacity and clay contents and -for clay soils- also to soil organic matter content (Schjønning et al., 1999) underpins high nutrient stocks and soil fertility of un-drained fine-textured clayey wetland soils.

A conversion of pristine wetlands into sites of agricultural production often comes along with drainage. Resulting aeration of wetland soils tends to enhance mineralization of soil organic matter (Grundmann et al., 1995; Thomsen et al., 1999) and negatively affects soil total C and N (Kamiri et al., 2013a). Therefore time series of moisture contents of wetland soils are an important tool for impact assessment on the hydrological regime of wetlands and thus on the crop production potential of these potentially highly productive ecosystems.

However, alterations of wetlands cannot be studied independently of their catchments (Giertz and Diekkrüger, 2003). A comprehensive analysis of the other components of the hydrological cycle of Tegu inland valley is ongoing whereby water table fluctuations will be related to soil moisture, climate and discharge data.

3.6 Conclusions

Our findings show that FDR systems can be used for reliable monitoring of soil moisture contents in inland valley wetland soils, with an error of 0.07 m^3/m^3. For a higher accuracy, a much larger diversity of moisture levels than in the present case must be represented in the dataset for field calibration. An extrapolation of these findings to wetland soils in general must be viewed with caution, as the range of soil attributes which might affect the response of capacitance sensors was low. We observed little variation of soil texture and bulk density between physical positions in the valley, and also between topsoil and subsoil. Only organic C contents were significantly lower at 40 cm below surface than above.

Even though specific site and soil conditions of the study wetland may be different in other wetland types (i.e. floodplain wetlands) and valley bottom lands in other climatic zones, the temporal variation of soil moisture was illustrated and a clear impact of land use on soil water dynamic was observed. The relationship between soil moisture and seasonal rainfall distribution was distinct for upland crops (mainly *Z. mays*). Levels of soil moisture were above field capacity for most of the time in the plot cultivated with arrowroot (*C. esculanta*). The chosen methodology for calibrating a FDR sensor for soil moisture monitoring in a wetland soil was successfully applied resulting in a reliable data base for process understanding required for wetland management.

3.7 Acknowledgements

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Chapter 4

Spatial and temporal water availability and management practices in an inland valley wetland in Kenya

This chapter has been submitted as Böhme, B., Becker, M., Diekkrüger, B., and Förch, G.: Spatial and temporal water availability and management practices in an inland valley wetland in Kenya, Wetlands, 2015.

4.1 Abstract

Small inland valley wetlands contribute substantially to the livelihood of rural communities in East Africa. Their conversion into farmland is driven by water availability. We quantified spatial-temporal dynamics of water availability in a headwater wetland in the humid zone of Kenya. Climatic conditions, soil moisture contents, groundwater levels, and discharge data were monitored. A land use map and a digital elevation model of the valley bottom were created to relate variations of soil moisture to prevailing land use types and valley morphology.

Upland crops occupied about a third of the wetland area, and the flood-tolerant taro, grown either sole or in association or in rotation with upland crops, about a quarter of the wet central part of the valley bottom. Furthermore, natural vegetation was found in 3% of the mapped area, mainly in sections with near-permanent soil saturation.

An overestimation of stream discharge during the long dry season of the hydrological year 2010/2011 by the HBV rainfall-runoff model can be explained by the strong seasonal impact of water abstraction on the wetland's water balance.

Our study demonstrated vividly the necessity of multi-method approaches for assessing the impact of management practices on water availability in valley bottom wetlands in East Africa.

Keywords: Colocasia esculenta, Digital Elevation Model, Land use mapping, Rainfall-runoff model, Soil moisture, Water abstraction

4.2 Introduction

Wetlands in East Africa provide a major proportion of the annual food needs of the wetland communities (Kangalawe and Liwenga, 2005) and contribute substantially to rural welfare (McCartney and van Koppen, 2004; Schuyt, 2005). With declining availability and quality of upland areas for agricultural production (Maitima et al., 2009), rural populations increasingly depend on wetland resources, especially during the "hungry" season (Dixon and Wood, 2003).

The projected climate change scenarios, particularly the increased spatial-temporal variability of precipitation (Collins et al., 2013; Giannini et al., 2008), may accelerate such trends, but also highlight the increasingly important future role of valley bottom wetlands as buffer systems (Wood and van Halsema, 2008).

Though small wetlands with less than 500 ha are much more abundant and cover a much bigger total area than the larger wetlands in East Africa, they have often been neglected by research (Mwita et al., 2013). Unlike for the West African inland valleys (de Ridder et al., 1997; Rodenburg et al., 2014), only few studies in the East African region are addressing the impact of land and management practices on the systems' hydrological regimes (Dixon, 2002). This gap may be attributed to scarcity of hydrological data and lack of information on land use patterns, among others.

In Kenya, freshwater wetlands cover between 3 and 4% of the country's surface area (National Environment Management Authority Kenya, 2009). The annual loss of wetlands, primarily due to drainage for agriculture, was estimated to be 7% (Gichuki, 1995). An understanding of hydrologic conditions in relation with prevailing land use types is required in order to prevent negative effects of management practices on the wetlands' ability to provide their diverse "ecosystem services" (Millenium Ecosystem Assessment Board, 2005).

Hydro(geo)logical wetland studies focus on water table fluctuations, time series of subsurface flow, or of river flow (Böhme et al., 2013). As the hydrological behaviour of wetlands is often controlled by processes in their catchments, lumped or semi-distributed conceptual rainfall-runoff models can be used to represent the effective response of the entire catchment, e.g. to climate and land use changes (Troy et al., 2007).

Particularly the amount, spatial distribution and the dynamics of plant available moisture in the rooting zone of wetland soils determine agricultural production potential directly (Worou et al., 2012), or indirectly through the control of nutrient dynamics (Bai et al., 2004). This hydrological parameter is influenced by land and water management practices, as well as by climatic conditions (precipitation, evapotranspiration), and by valley morphology controlling runoff and depth of groundwater table. Therefore, soil moisture can serve as an integrated indicator of alterations of a wetland's hydrological regime.

Our paper aims to assess water availability in relation to land use and agricultural management practices, as well as morphology, in a groundwater inland valley wetland of the humid zone of Central Kenya. The main objectives of the study were:

- to describe the land use and morphology of the inland valley bottom,
- to characterize its hydrological regime, and
- to assess spatial and temporal soil moisture variations in context with the morphology of the valley bottom.

For this purpose, we generated a land use and elevation map of the valley bottom. This information was combined with *in-situ* measurements of soil moisture and groundwater levels. A semi-distributed rainfall-runoff model was applied to relate the catchment's hydrological response to rainfall events with the wetland's stream discharge.

4.3 Materials and Methods

4.3.1 Study area

The study site was Tegu valley, one of the small wetlands that are generally found in higher rainfall areas of Western and Central Kenya (Howard, 1992). The wetland of Tegu Stream lies at 1720-1840 m altitude in the upper reaches of Tana River, south of Mount Kenya (Figure 4.1).

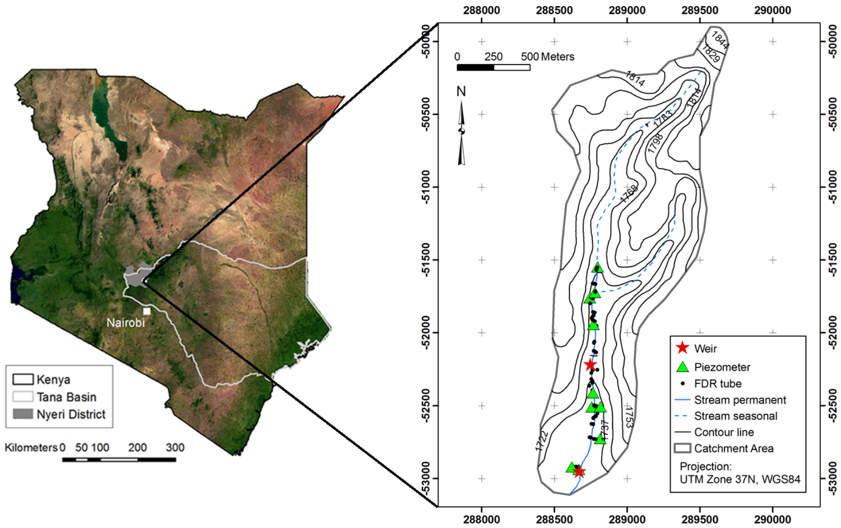


Figure 4.1: Location and topography of the Tegu inland valley in Central Kenya, Nyeri district.

Underlying geology is part of the pleistocene Mt. Kenya volcanic series from the main eruptive episode of Mt. Kenya (Baker, 1967). Trachytes, olivine trachytes and mugearites can be found at the southern slopes of Mt. Kenya in the area of Tegu valley. Annual rainfall occurs in a bimodal pattern with a total of about 1450 mm (Jaetzold et al., 2006) and mean temperature is between 15 and 20° C°C (Nyeri meteorological station).

For the purpose of this study, we are applying the definition of Andriesse et al. (1994, p.159) for inland valley wetlands. They are defined as "upper reaches of river systems, comprising valley bottoms and minor floodplains which may be submerged for part of the year, their hydromorphic fringes, and contiguous upland slopes and crests".

In terms of vegetation ecology, the study area is assigned to the class of marshes (Tiner, 2009), which are "dominated by herbaceous vegetation and flooded for all or most of the growing season or periodically". This is in agreement with the classification of Ramsar Convention, where the study area falls into the class of permanent freshwater marshes (Ramsar Convention Secretariat, 1994).

The catchment area of the stream headwater wetland comprises 2.3 km^2. Steep slopes margin the valley bottom with inclination ranging from 5 to 36%. Upland soils are classified as Nitisols with clay content of about 50% and sand content of about 40% (Kamiri, 2010). They are used for cultivation of coffee, diverse food crops and napier grass (*Pennisetum purpureum*). Exotic (*Graveria* spp., *Eucalyptus* spp.) and native (*Prunus africana*) tree species are commonly encountered. Homesteads with home gardens (with vegetables and fruit trees) are located in the upper slopes. Average farm size is 1.02 ha, and average wetland field size is 0.22 ha (Sakané, 2011).

The deep and poorly drained Dystric Fluvisol of the valley bottom contains between 54% and 79% clay (Böhme et al., 2013). Therefore, the study site fulfills the criteria of riverine wetlands which develop due to impeded drainage in the valley bottom. While the water flow in the central river bed is permanent, it is seasonal in the upstream valley head. Farmers established a network of small canals in order to divert excess water or to allow for irrigation. Further detailed information on the biophysical characteristics of Tegu inland valley have been published in Böhme et al. (2013), Kamiri (2010) and Sakané (2011).

Few portions of the valley bottom wetland were not cultivated during the field campaigns (2009-2011) and either left fallow or were covered with natural wetland vegetation (mainly *Cyperus* spp.).

The majority of the valley bottom land is cultivated with subsistence food crops (mainly maize, *Zea mays*), with taro (*Colocasia esculenta*) for market and for own consumption, and with diverse horticultural crops (mainly *Brassica* species). As the production of maize in the valley bottom is constrained by high water tables, maize is usually produced by cultivation on raised beds.

Taro is cultivated in wet culture. Land preparation for taro is labour intensive and involves clearing, ploughing and puddling. Vegetables are mainly cultivated along the well-drained valley fringes. Fish ponds have been constructed in 2010 downstream of the upper weir (Figure 4.1) in order to provide additional sources for income generation for the wetland communities. Through its closeness to Karatina municipality with one of the largest open markets in Sub-Saharan Africa, farmers of Tegu wetland have a good market access to sell their products.

4.3.2 Digital Elevation Model (DEM)

For describing hydrological processes in the inland valley, a DEM at sufficient resolution was required. The only elevation database available is from Shuttle Radar Topography Mission (SRTM) with a spatial resolution of 3" (NASA, 2014), ASTER DEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model) (NASA, 2009) with a spatial resolution of 30 m, and topographic maps at the scale of 1:50 000 (Survey of Kenya, 1974).

In order to address this limitation, we sampled 23 ha of the bottom and fringe/lower slope of Tegu valley using geometric leveling with a bubble precision level (TOP CON AT-xxx) to determine differences in height (Torge, 2012). The leveling was carried out in March-April 2010, thus at the onset of the long rains, with equal back and foresights at less than 15 m distance for eliminating systematic errors.

Over 2000 points were sampled in 115 transects across the valley bottom starting from the stream at the centre of the valley towards the fringe.
The transverse transects were connected through leveling along the stream in order to determine longitudinal elevations. Distance between points within the transects was 2.5-10 m, distance between transects 20-40 m. The upper weir (Figure 4.1) was used as reference point for all other sampling points.

The terrain geometry was generated from sample points using Triangulation algorithm in Esri ArcGIS 10.1. The inclinations of the generated survey-TIN were used for differentiation between the central part of the valley bottom and fringe/lower slope. Those areas with inclinations of less than 4% were assigned to the central valley bottom, the remaining proportions to the fringe and lower slope, respectively.

4.3.3 Land use map

With regard to moisture requirements, flooding tolerance, and growing periods of common crops in tropical highlands, we characterized the land use types of the study area as displayed in Table 4.1. For each sampling point used for DEM generation, the major land use was recorded and classified.

1. The only major food crop grown under the flooded conditions of the valley bottom is taro (*Colocasia esculenta*). Taro can tolerate heavy soils, has a high water demand and requires saturated soil conditions for up to 9 months. However, for tuber formation and harvest it depends on dry or well-drained soil conditions.

2. The cultivation of upland crops, mainly maize (*Zea mays*), in combination with wetland crops, mainly taro, is either limited to the dry season, to well drained valley fringe areas or to the main wetland, provided drainage facilities are in place. As maize does not tolerate flooding, crop growth is only possible where the flooding period is $<$6 months and the soil moisture content (SM) is between Permanent Wilting Point (PWP) and Field Capacity (FC) for the growing period.

3. Cultivation exclusively with upland vegetables and maize is only possible in areas without flooding and soil moisture contents between Permanent Wilting Point (PWP) and Field Capacity (FC) for $>$9 months.

4. Areas dominated by natural vegetation, or used for ruminant grazing or as fallow land are found in areas where either soil moisture is too heigh for cultivation, where physical access to the wetland is restricted, or farmers abandon the plot for other reasons, such as lack of labour.

5. Forage grasses, mainly napier (*Pennisetum purpureum*), are grown under strictly aerobic conditions or in wetland areas with $<$3 months of flooding. They are mainly found in steep areas without stream discharge, such as in the valley head.

Fruit trees, timber trees and mixed forest as well as shrubs were assigned to the class “trees and shrubs”. Land uses others than those (e.g. bare ground, channels, sugarcane) listed above were assigned to the class “others”.

Table 4.1: Relationship between flooding regime and land use in the inland valley of Tegu, Kenya. SM=soil moisture content, PWP=Permanent Wilting Point, FC=Field Capacity.

	Land use type		
Flooding regime	Food Crops	(Semi-)Natural vegetation	Non food crops
Soil saturation for $>$9 months	-	(4) Natural veg.	-
Soil saturation for 6-9 months	(1) Taro		-
Soil saturation for $<$6 months	(2) Upland crops/Taro	(4) Grazing/Fallow	-
Soil saturation for $\ll$6 months, and PWP$\leq$SM$\leq$FC for $>$9 months	(3) Upland crops (Maize/Vegetables)		(5) Napier grass

To determine the proportion of each land use class, each sample point was weighted with the distance to its neighbor. We calculated land use proportions for the whole mapped area (including the central valley bottom and fringe/lower slope) and for the central valley bottom separately.

Additionally, we counted how many man-made drainage channels we crossed along one transect in the central part of the valley. Drainage intensity for each transect along Tegu valley was expressed as mean counts of drainage channels over a reference transect length of 100 m.

The optimal type of use for a specific location as predicted from the moisture status at the monitoring site ('FDR-site', Frequency Domain Reflectometry) was compared to the dominant land use at the respective site during the monitoring period in 2009-2011. Points with fallow were excluded from this validation as fallows were found across the various moisture regimes.

4.3.4 Hydrological monitoring and modelling

The set-up of the hydrological monitoring network is described in detail in Böhme et al. (2013). Fifty-two locations within Tegu wetland were monitored for soil moisture content over a period of 21 months (2009-2011). We used a Frequency Domain Reflectometry (FDR) Profile Probe (Delta-T Devices Ltd, 2008) which was calibrated site specifically and used for portable readings at soil profile depths of 10, 20, 30, and 40 cm. The diversity of prevailing land uses, geomorphological characteristics (central part, valley fringe, lower valley slope), and hydrological regimes (drained vs. undrained) was covered.

Two V-notch weirs, one in the mid and one in the lower section of the valley, were installed for measurement of stream discharge and for estimation of water uses and/or sources within the inland valley (Figure 4.1). The data from the lower weir were not viable due to frequent overflow and bypass during wet season.

Furthermore, the wetland was instrumented with ten piezometers for monitoring of groundwater level. The 2 m pipes were perforated at the lower tip over a length of 30 cm.

A full-automatic weather station capturing rainfall, temperature, wind speed and direction, relative humidity and solar radiation as well as topsoil temperature was set up at the valley slope. Additionally, a Hellmann rain gauge collected daily precipitation. Reference evapotranspiration and crop water requirements were calculated according to FAO standard (Allen, 1998).

To study general hydrological behaviour, the daily semi-distributed rainfall-runoff model HBV light (Seibert and Vis, 2012) was applied for streamflow simulation for the period 11/2009-10/2011. The model considers a soil and two groundwater layers. Daily rainfall and daily potential evapotranspiration are used as input data.

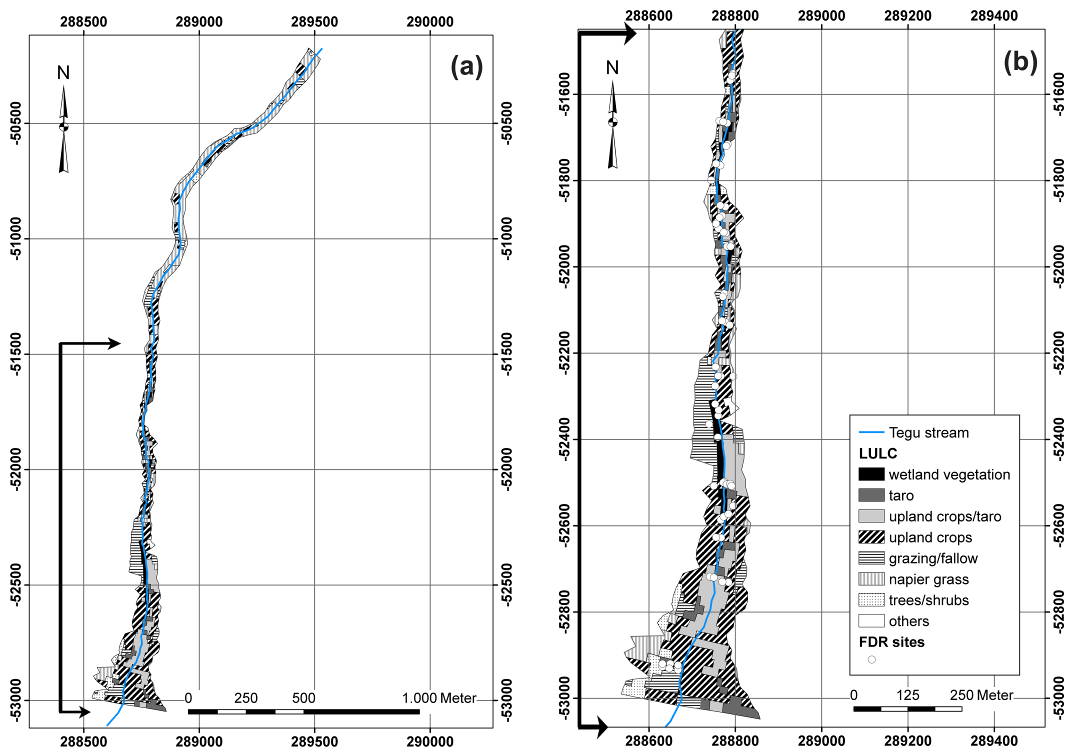
Four model parameters have to be optimised: the soil field capacity, a threshold for reduction of evaporation, and two groundwater recession coefficients. Different efficiency criteria can be used to assess model performances whereby we used the Nash-Sutcliffe criterion calculated on the logarithm transformed streamflow that emphasizes the quality of low flow simulation (Seibert, 2000). Parameter values can be optimized using a genetic calibration algorithm included in HBV light, given that an efficiency criterion has been selected.

We used five years of warm-up period and two years (November 2009-October 2011) for simulation. The size of the sub-catchment from valley head to the selected discharge weir (upper weir as shown in Figure 4.1) was 1.75 km^2.

4.4 Results

4.4.1 Land use and morphology along the upland-lowland continuum of the inland valley

The inland valley of Tegu stretches over a distance of 3100 m in North-South direction (Figure 4.2). Each transect (see Figure 4.3b) covered a cross section reaching from the central valley bottom/drain over the valley fringe to the lower hill slope. Maximum transect length was 320 m and minimum length was 20 m, measured about 250 m south of the stream source (Figure 4.4).



(a) (b)

Figure 4.2: Land use and land cover (LULC) in the inland valley, Kenya: (a) Overview. Polygons created from survey points; (b) Detailed LULC map with locations of sites equipped with Frequency Domain Reflectometry (FDR) tubes.

Figure 4.2 and Table 4.2 provide the information on the coverage of the prevailing types of land uses. Plots with purely upland crops, such as maize, beans or vegetables, occupied about a third of the wetland area. Taro, grown either sole or in association or in rotation with upland crops, is largely concentrated in the wet central part of the valley bottom and accounts for about 25% of that area. Accounting also for the fringe/lower slopes, the proportion of a taro-based land use covered only 14% of the wetland.

Napier grass was more abundant on the well-drained (lower) valley slopes with 29% for the whole surveyed area. Natural vegetation, on the other hand, was mainly found in the wet valley bottom, covering 6% of the central wetland part or 3% of the total mapped area.

Table 4.2: Proportion of different land uses in the Tegu inland valley, Kenya. Whole survey area (central valley bottom and fringe/lower slope) and survey area located in central valley bottom only are differentiated. *not equal to 100% due to rounding.

	Proportion in area	
Land use	Whole area (Central valley + Lower slope) %	Central valley %
Wetland vegetation	2.6	6.3
Taro	5.8	9.8
Upland crops/Taro	8.5	15.6
Upland crops	29.8	29.4
Grazing/Fallow	13.6	11.9
Napier grass	28.7	19.4
Trees and shrubs	6.1	2.5
Others	4.8	5.2
Sum	99.9*	100.1*

The valley bottom ratio (VBR), i.e. the ratio of the area of the higher valley parts (valley fringe, slopes and crests) over the area of the valley bottom is 9. The central part of the bottom with less then 4% inclination occupies about 44% of the valley bottom area.

The valley was subdivided longitudinally into the upper, the mid, and the lower valley section (Figures 4.3 and 4.4). The main stream of Tegu with a well defined channel originates at about 1500 meters distance from the lower weir which is defined as outlet point of the catchment.

In the floodplain-like *lower* section, taro was widespread and mainly cultivated in association or rotation with upland crops (Figures 4.3 and 4.4). Cultivation of upland crops is only possible through human-made drainage channels and cultivation on raised beds. The highest density of drainage/irrigation channels was encountered in the *lower* and in the wet *mid* section of Tegu valley where taro was most common (Figure 4.4).

In the bowl-like shaped valley head and in the narrow *upper* section, the central valley floor is only seasonally wet or water-saturated (Figure 4.3). Channeling was not noted. In this area, the cultivation of napier grass as a fodder plant prevailed.

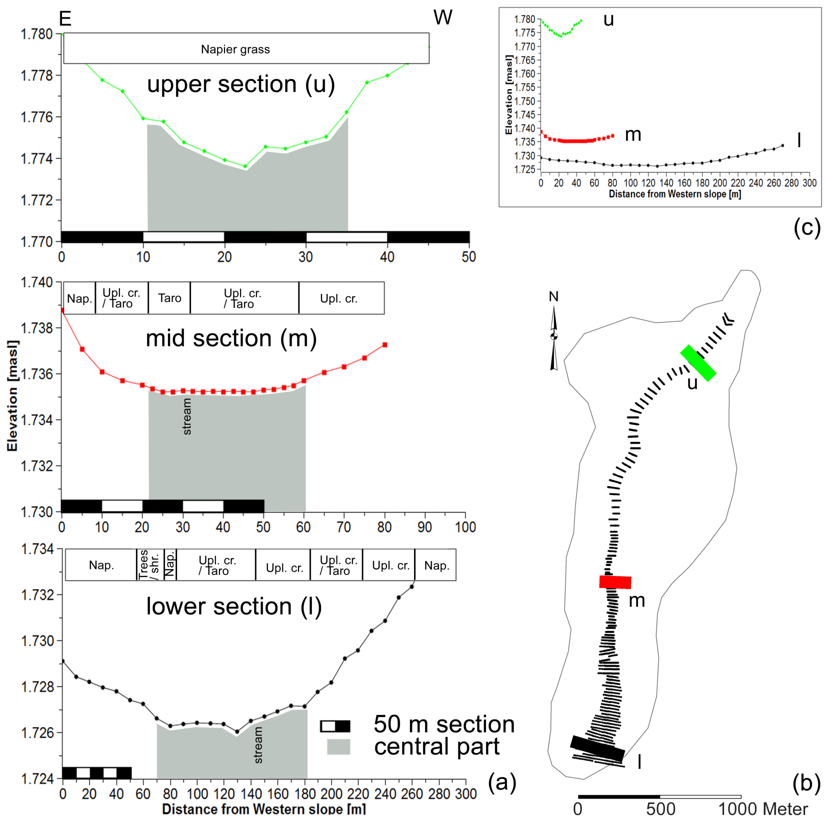


Figure 4.3: Land use and morphology at selected cross-sections of the inland valley, Kenya: (a) From top to bottom: upper section (transect at 2800 m distance from valley outlet), mid section (transect at 1160 m distance from valley outlet), and lower section (transect at 80 m distance from valley outlet); scale fitted; (b) Location of all transects in valley bottom. Positions of transects from sub-figure (a) are indicated with bold bars; (c) Cross-sections from sub-figure (a) drawn at same scale for ease of comparability of size; Nap. = Napier grass, upl.cr. = upland crops, Trees/shr. = Trees/shrubs.

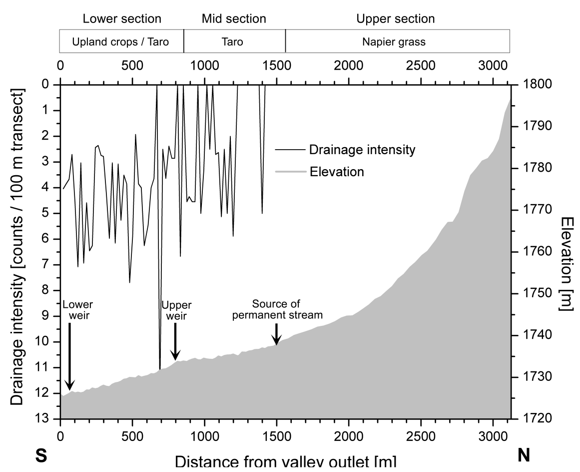


Figure 4.4: Longitudinal transect along the inland valley, Kenya, from South (S) to North (N). Drainage intensity expressed as mean counts of drainage channels over a reference transect length of 100 m.

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4.4.2 Descriptive agronomy and hydrology

The combination of the land use map (Figure 4.2) and groundwater levels with the time series of volumetric soil moisture content θ yields in four types of patterns (Figure 4.5). Only soil moisture content at 10 cm depth is considered as it shows the largest differentiation between sites.

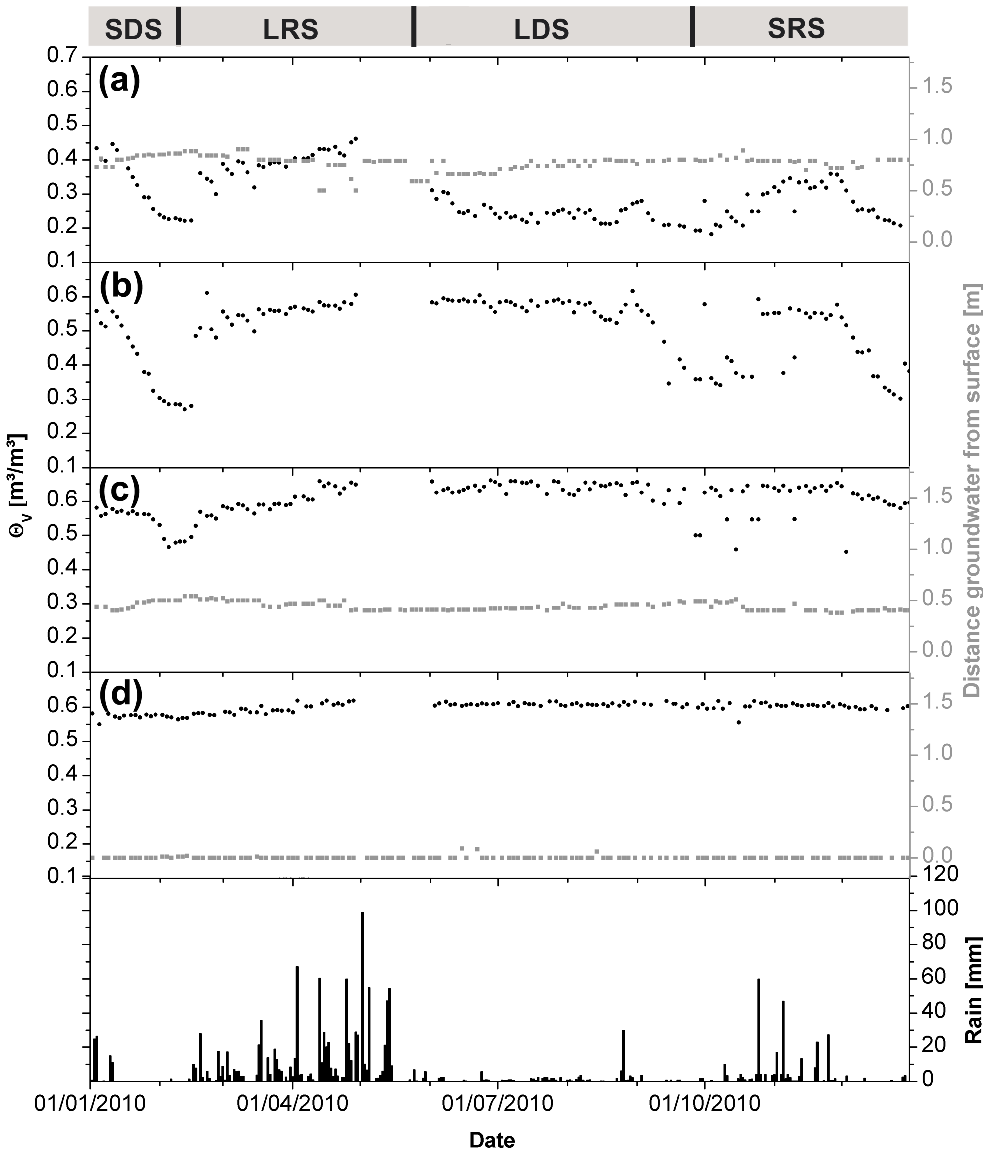


Figure 4.5: One-year time series of daily rainfall plotted against volumetric soil moisture content θ in topsoil (10 cm) (left y-axis, black data points), and against distance of groundwater table to soil surface (right y-axis, grey data points). Inland valley, Kenya. Four selected sites are displayed with increasing duration of soil saturation from (a) to (d). For sub-figure (b) no data for distance of groundwater table to ground surface available. SDS = Short Dry Season, SRS = Short Rainy Season, LDS = Long Dry Season, LRS = Long Rainy Season.

Soil moisture contents were close to saturation (approximately 0.6 m^3/m^3) throughout the year in the central valley bottom (Figure 4.5(d)), supported by a high groundwater level with negligible seasonal variation. Where soil saturation exceeded 9 months duration, mainly natural wetland vegetation was encountered.

Soil flooding and anaerobic conditions for extended periods limit the growth of upland crops unless agricultural management measures such as cultivation on raised beds, or soil drainage are applied. This case is displayed in Figure 4.5(b).

The cultivation of taro was most abundant in valley positions with flooded/saturated conditions for up to 9 months (Figure 4.5(c)). Annual variations of soil moisture content along the lower slopes were higher than in the valley bottom, with the permanent wilting point (approximately 0.2 m^3/m^3) being reached towards the end of the long dry season (Figure 4.5(a)). There, the distance of the groundwater table to soil surface was >0.5 m. Thus, the main water source for surface soil moisture was rainfall and the cultivation of upland crops was feasible.

Extrapolation of areas with a) hardly ever occuring soil saturation ($\ll$6 months), b) soil saturation for less than 6 months per year, and c) more than 6 months per year, yields in Figure 4.6. The resulting area percentage of each class as compared to the total valley bottom area is 29%, 40%, and 31%, respectively.

Time series of soil moisture contents of all monitoring sites have been assigned to the land use types described in Chapter 4.3.3. The most appropriate land use type (cropping system) with regard to flooding tolerance and soil moisture requirements has been derived for each FDR site according to Table 4.1.

For the majority of cases (34 out of 53 cases), the actual land use did not agree with the optimal use (Figure 4.7). Soil moisture status tended to be too wet for the actual use. The best agreement was noted for sites under upland crops in combination/rotation with taro. Most sites where the cultivation of upland crops was feasible as concluded from the soil moisture status at the FDR site (i.e. extended periods without soil saturation/flooding), were actually used to grow upland crops. On sites where cultivation of taro is advisable, farmers still attempted to cultivate upland crops (partially intermixed with taro), risking crop failure due to flooding. Sites where soil saturation exceeded duration of nine months should have been left to fallow or under natural vegetation. However, in most cases, these sites were cultivated with taro.

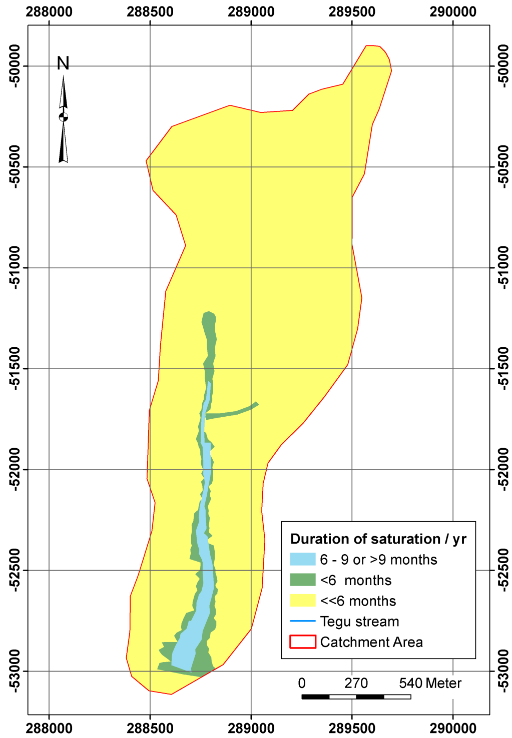


Figure 4.6: Coverage of areas with hardly ever soil saturation ($\ll$6 months), with less than 6 months soil saturation, and with more than 6 months soil saturation. Inland valley, Kenya.

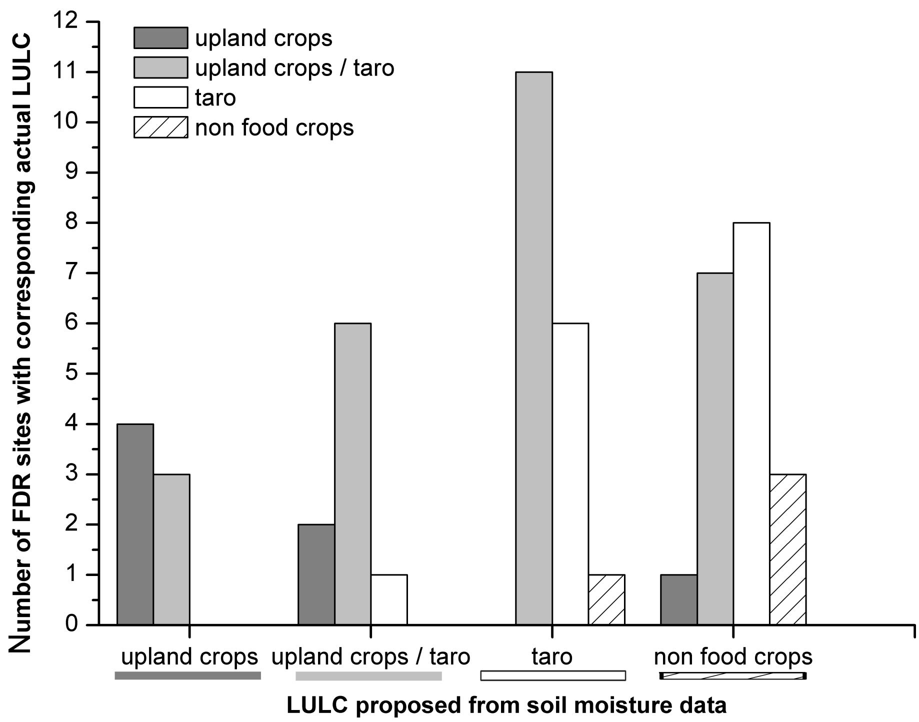


Figure 4.7: Actual land use and land cover (LULC) at Frequency Domain Reflectometry (FDR) sites compared to LULC as proposed from soil moisture time series. Inland valley, Kenya. Bar size represents number of FDR sites for each combination.

4.4.3 Explanatory hydrology-results from rainfall-runoff modelling

The total amount of rainfall of the period 01/11/2009 to 31/10/2010 was 1416 mm while it was 1007 mm for the same period in 2010/2011. Potential evapotranspiration was about 1230 mm in both years. In the wet year 2009/2010 runoff coefficient was about 16% while it was only 7% in the dry period 2010/2011. This general difference between the two years was confirmed by HBV light (Figure 4.8).

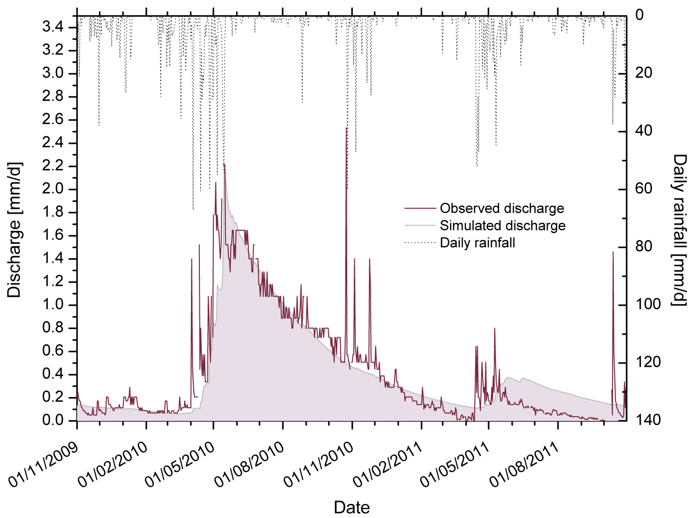


Figure 4.8: Output of HBV light daily rainfall-runoff model for the inland valley, Kenya. Years 2009-2011. Coloured area represents simulated discharge.

Even though single peaks were not simulated adequately, the general hydrological behaviour was simulated satisfactorily for the year 2009/2010. Simulated discharge is in the same order as the observed. The Nash-Sutcliffe criterion of 0.8 confirms a good simulation result. For the period 2010/2011, discharge is overestimated significantly by about 30% (90 mm simulated vs. 68 mm observed) even though the general dynamic (recession of discharge) is simulated well. Rainfall in this period is much below water demand for crop production which in this case requires supplementary irrigation which was not the case for the first period.

Assuming that differences between simulated and observed discharge can be explained by water abstraction for irrigation, 22 mm discharge which equals 38500 m^3 have been used. Within a vegetation period of 90 days this equals 430 m^3/day. Using this figure, we determined the potential irrigation area for an unspecific vegetable. Reference evapotranspiration was set to 2.2 mm/day. A uniform crop coefficient of '1' was applied for the calculation of crop evapotranspiration. After depletion of soil water storage a supplementary irrigation of 2.2 mm/day will be required.

Thus, the amount of water which was uncaptured by the HBV model would be sufficient for vegetable irrigation on 11% of the catchment area of Tegu over one growing period.

4.5 Discussion

In this paper we investigate the linkages between land use patterns, morphology, hydrological conditions and agricultural management practices in the inland valley of Tegu in the humid zone of Central Kenya. The land use map represents the wetland's status in March-April 2010, just before the onset of the long rains. At this time, a quarter of the mapped central valley bottom (<4% inclination) was cultivated with purely taro (*Colocasia esculenta*) or taro in combination/rotation with upland crops.

Taro is a crop which has been grown for a long time in the bottoms of the region's headwater wetlands (Gichuki, 1992). Though taro is best adapted to very wet or flooded conditions of more than 6 months (Lebot, 2009), decreases in yield have to be expected if soil saturation lasts longer than 9 months. Cultivation on raised beds to avoid waterlogging of the rooting zone or implementation of a low intensity drainage where excess water is only evacuated during vegetative growth periods would be sufficient for taro cultivation (Gichuki, 1992). The crop's potential to contribute to food and income security in the East African region is still underutilized (Talwana et al., 2009) and it is well suited for wetland cultivation.

According to our survey, plots with purely upland crops occupied about a third of the wetland area. Unless plots are established on raised beds providing a larger distance to the prevailing shallow groundwater table, cultivation of upland crops is to be limited to the valley fringes/lower slopes where periods of more than 9 months without soil saturation were observed. Areas with extensive waterlogging, such as the narrow mid section of Tegu valley with its flat valley bottom and concave slopes, should be left fallow.

Generally, soil moisture status in Tegu inland valley wetland tended to be too wet for the actual use. For example, purely upland crops were grown in areas with more than 6 months of soil saturation, whereby farmers are risking anaerobic stress for the crops and loss of the harvest (Zaidi et al., 2012).

Extension of the drainage network in the floodplain-like lower section of the valley with the aim to control soil moisture regime in the crop rooting zone would be required to expand production of high value crops. We showed that the density of the network of drainage/irrigation channels is highest in the lower and mid section of Tegu valley.

However, an intensification of drainage bares the risk of a depletion of the groundwater table and alterations of stream flow. For a detailed assessment of impacts from wetland management practices on stream discharge, water flow in the channel network would have to be quantified (Acreman and Holden, 2013).

For groundwater wetlands, these effects can be studied through the application of a distributed hydrogeological model, for example MODFLOW (U.S. Geological Survey, 2000), which is able to accomodate the dual purpose of drains: draining excess water during the wet season and routing water into the plots during dry season.

A shallow groundwater level controls soil moisture status and hence agricultural production potential of crops with a high water demand, e.g. taro. Drainage of wetland soils tends to enhance mineralization of soil organic matter (Grundmann et al., 1995) and negatively affects soil total C and N (Thomsen et al., 1999). Therefore, the inland valley wetland of Tegu can loose its wetland characteristics if excessive drainge measures are established without precautions.

Against the background of an estimated annual wetland loss of 7% in Kenya, primarily due to drainage for agriculture (Gichuki, 1995), the results of our study can be put in the context of regional development. Currently, only 3% of the mapped wetland area is covered with wetland vegetation. This is considerably less than the 16% detected by Mwita (2010) in a remote sensing study on inland valleys in Mt. Kenya region.

The application of a semi-distributed rainfall-runoff model demonstrated the strong seasonal impact of agricultural interventions, such as water abstractions, channel blockage, and stream deviation, on stream discharge. This impact can not be fully accounted for due to lack of information on irrigated area, irrigation schedules and amounts abstracted. Still, our estimation of irrigation water demand provides a plausible explanation for the reduction of stream discharge during the dry season. Uncontrolled abstraction potentially pressurizes downstream communities who depend on upstream water sources.

Our data provide the base for further evaluation of the ecological condition of Tegu wetland and the sustainability of its use. The WET-Health (Macfarlane et al., 2009) and WET-Sustainable Use framework (Kotze, 2010) are useful tools for addressing this task through examination of five major wetland components[1] as demonstrated by Kotze (2011) for three wetlands in Malawi.

[1] These components are: hydrology, geomorphology, accumulation of soil organic matter, nutrient retention and cycling, vegetation composition

Considering the fact that 35% of the total land area of Kenya experiences severe climate constraints for rain-fed crop production, most of them related to moisture deficits (Fischer et al., 2002), an appropriately planned cultivation of suitable inland valley wetlands, based on sound scientific data and experience of local communities, can be seen as a means for providing food security to local communities while at the same time serving the water requirements of the ecosystem.

4.6 Conclusions

Characterization of the hydrological processes in the small headwater inland valley wetland of Tegu required an understanding of its morphological setting and prevailing land use types.
Therefore, a hydrological database was established and a land use map as well as a digital elevation model of the valley bottom were created. We found that time series of soil water content were interrelated with landscape position. Generally, actual land use is not fully adapted to soil moisture status in the study area.

Farmers attempt to cultivate upland crops (partially intermixed with taro) on sites were cultivation of taro only may be more advisable. Hence, they risk crop failure due to flooding. Still, taro was widely cultivated in the valley bottom. It is well suited for wetland conditions and has a large potential to contribute to food security in the region.

The application of the HBV rainfall-runoff model proved of value for assessing the impact of irrigation water abstraction on the wetland's stream discharge.
All over, our multi-method approach and the gained results are seen to contribute scientific knowledge to a more 'people-centered wetland management' in the East African region.

4.7 Acknowledgements

This research was funded by the project "Capacity Building for Integrated Watershed Management in Eastern Africa (IWMNet)" through the 9^{th} European Development Fund (EDF), ACP-EU Water Facility. The research project was conducted within the framework of the project "Agricultural Use and Vulnerability of Small Wetlands of East Africa (SWEA)" supported by the Volkswagen Foundation, Hannover, Germany. We also acknowledge the support of Biomechanical & Environmental Engineering Department at Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya. We are very grateful for the support from Lucy Njoroge, Joseph Ndiritu, Godfrey Wachieni and Peter Kimotho during field work.

Chapter 5

Evaluating crop production potential in a floodplain wetland in Tanzania: The challenge of soil moisture monitoring

This chapter will be adopted and submitted to Physics and Chemistry of the Earth, Parts A/B/C.

5.1 Abstract

Information on spatial and temporal water availability for crop production is indispensable for land use planning in wetlands. Crops greatly differ in their growth duration and moisture requirements with 4 months of soil flooding in the case of rice and >3 months of moist but free-draining aerobic soil conditions for maize and most vegetables. However, the characterization of complex hydrological processes poses a challenge in data-scarce regions such as East Africa. We quantified soil water availability in the plains of the Mkomazi River in the sub-humid lowlands west of the Usambara Mountains, Tanzania. Based on landscape position and the major water sources for replenishing soil water reserves (river flooding, shallow groundwater, ponding of rain water), we differentiated five major sub-units of land use: (1) natural vegetation; (2) dry season grazing land; (3) rainfed rice during the wet season and vegetables during the dry season; (4) irrigated rice with occasional vegetable cultivation; and (5) upland crops.

At selected sites within these sub-units, biophysical characteristics were determined. Hydro(geo)logical and meteorological variables, including groundwater levels, and Frequency Domain Reflectometry-based soil moisture contents were monitored over 2 years. The swell-and-shrink behaviour of the predominating Vertisol impeded continuous monitoring of soil moisture, causing gaps in the time series.

To close these gaps, we applied the HYDRUS-1D software package to simulate the hydrological relationship between climate conditions and seasonal soil water storage, allowing the assessment of the length of growing period (LGP) as indicator for land suitability and upland crop production potential, or the length of flooded/saturated soil conditions for lowland rice cultivation.

In the central floodplain, flooding of the river, ponding of rainwater as well as seasonally high groundwater levels are replenishing soil water storage. An annual cumulative water loss from the soil profile of about 360 mm was calculated for the lowland rice, and the duration of soil saturation was determined to be 115 days. In the fringe areas of the wetland with rain as the only water source, an accumulated increase of 250 mm soil water storage was calculated for the observation period. The cultivation of most upland crops is possible due to the duration of moist soil conditions for 115 days. While soil water storage after flood recession may allow the cultivation of short-cycled upland crops following lowland rice in the floodplain center, soil water storage in the fringe areas is insufficient for dry season cultivation.

This hydrological characterization is seen to improve the targeting of crop uses in floodplain wetlands and can guide future wetland use planning in the region.

Keywords: HYDRUS-1D, Floodplain, Length of growing period, Soil water balance

5.2 Introduction

The majority of the population in East Africa depend on rainfed agriculture for staple food production. In Tanzania, irrigation potential is estimated to be 29.4 million ha (Tanzania Ministry of Water and Irrigation, 2009). However, only about 1.5% of the potential area had been developed by the end of 2013 as reported by the Ministry of Agriculture, Food Security and Cooperatives. Due to their water availability and their large size and abundance, floodplain wetlands in particular are increasingly becoming the focus of agricultural development projects in view of attaining food security under variable climate conditions. Thus, in the Kilombero River Basin, substantial increases in rice production and in the area under sugarcane have been recently reported (Kato, 2007; Munishia and Jewitt, 2014). The basin hosts a Ramsar wetland site and is one of the target areas of the Southern Agricultural Growth Corridor (Southern Agricultural Growth Corridor of Tanzania, 2014).

Approximately 10% of Tanzania's country area is covered by wetlands (Kamukala, 1993), whereby permanent and seasonal freshwater swamps, marshes and seasonal floodplains constitute 2.7 Mio ha.

Crop-specific soil moisture requirements together with soil and terrain data and data on spatial-temporal water availability are typically used for detailed assessments of a site's suitability for agricultural production and estimation of potential and actual crops yields. Such approaches are implemented in FAO's Agro-Ecological Zones (AEZ) concept (FAO, 1978) and are incorporated in FAO's Aqua Crop Model (FAO Land and Water Division, 2011). Particularly the amount and the dynamics of soil moisture in the rooting zone is the key to crop growth and determines the suitability of wetlands for crop production.

Additionally, the site's biophysical characteristics have to be understood for the evaluation of potential impacts of agriculture-related water and land management interventions on the ecosystem's service provision capability (Kotze, 2011, 2010).

High resolution and good quality time series of hydrological variables are required for appropriate land use planning. However, these data are rarely available and gaps in time series are frequent due to interference with measurement devices, the inaccessibility of sites during flooding periods or the malfunctioning of devices.

In distributed soil moisture data sets, statistical and data-driven methods are an option for filling in missing values (Kornelsen and Coulibaly, 2014). Remotely sensed soil moisture data may serve the same purpose as they are widely used for quantification of field-scale soil water dynamics (Robinson et al., 2008). Alternatively, soil water models, describing the interactions between meteorological conditions, land cover and seasonal soil water storage are capable of overcoming limitations caused by data gaps at a point.

The HYDRUS-1D computer program (Šimůnek et al., 2008) has been applied for the evaluation of water movements and solute transport in soils under various land covers and in diverse climatic regions, including drained peatland soils (Schwärzel et al., 2006), grazing areas in semi-arid environments (Chen et al., 2014), lowland rice in subtropical monsoon climate (Li et al., 2014) and maize production in a dry sub-humid to semi-arid environment (Ramos et al., 2011).

This study aims to determine the soil water availability in the plains of the Mkomazi River in the sub-humid lowlands west of the Usambara Mountains, Tanzania. Our specific objectives were (i) to distinguish different sub-units of land use within the floodplain according to geomorphic setting and the dominant water source (sub-surface water, surface water); (ii) to describe factors controlling soil moisture status, including rainfall attributes, soil texture, soil layering, vegetation, and groundwater depth; (iii) to monitor volumetric soil moisture content in the rooting zone using a site-calibrated capacitance soil moisture sensor; (iv) to apply the soil-water model HYDRUS-1D for simulation of the hydrological relationship between climate conditions and seasonal soil water storage, thereby closing the data gaps in time series of measured volumetric soil moisture contents and (v) to conclude for a site's suitability for crop production in relation to the length of growing period (LGP) concept (FAO, 1978).

5.3 Materials and Methods

5.3.1 Study area

The Malinda floodplain is located in the Tanga region, Korogwe District of Tanzania (Figure 5.1). The plains lie at about 360 m a.s.l. in the tropical lowlands at the western leeward side of the Usambara Mountains. The floodplain has an area of approximately 11 km^2 while the area under investigation comprises 7.8 km^2, extending between latitudes 5°4'29"-5°7'14"S and longitudes 38°19'16"-38°21'36"E. It is drained and seasonally inundated by the Mkomazi River which feeds into the Pangani river. The Mkomazi River originates on the eastern slopes of the Pare Mountains. Its discharge is considered unreliable and the river may dry up towards the end of the dry season (Agrar- und Hydrotechnik GmbH, 1976c,d). The Soni river and the Vuruni river are important tributaries of the Mkomazi River. The sub-catchment area, in which the Malinda floodplain is located, covers approximately 321 km^2 (Agrar- und Hydrotechnik GmbH, 1976e).

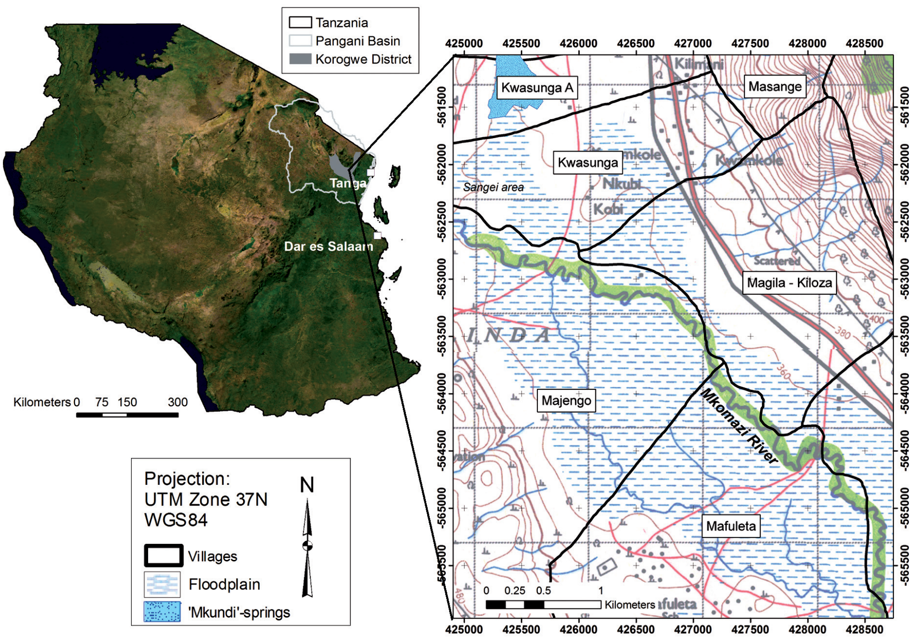


Figure 5.1: Location of Malinda floodplain wetland in Tanzania (Tanzania map data from Map Library, 2013, topographical map from Ordnance Survey of the UK, 1988).

The valleys of the Mkomazi and Pangani Rivers are of tectonic origin, whereby the tectonic graben in which the Pangani flows is older and at a higher elevation than that of the Mkomazi River (Agrar- und Hydrotechnik GmbH, 1976e). The parent material in the level plains are superficial unconsolidated alluvial sediments of quaternary age. Usagaran rocks consisting of gneisses are the geological base of the adjacent uplands (Agrar- und Hydrotechnik GmbH, 1976a).

The valley bottom of the Mkomazi River can be subdivided “into river, levees, backswamps, clay plains slightly above backswamp level, irrigated lowlands and salt flats” (Agrar- und Hydrotechnik GmbH, 1976a, p.6.2). Alluvial fans mark the transition between the valley bottom and the adjacent uplands. Springs are emerging from the foothills of the Usambara mountains east of the study area. Within the wetland area, a shallow groundwater table in Kwasunga A-area results from numerous springs as displayed in Figure 5.1. Additionally, the location of 'Sangai area' in a kind of depression favours influx of ground- and surface water, thus creating an environment for development of natural wetland vegetation comprising typha (*Typha domingesis*) and papyrus (*Cyperus papyrus*). Fine textured Vertisols, Fluvisols and Gleysols are the prevailing soil types in the plains (Kamiri et al., 2013b). They tend to crack upon drying and experience ponded drainage once the soil is swollen and cracks are reduced. The dominant soil group of the adjacent upland areas is Ferralsol (FAO, IIASA, ISRIC, ISSCAS, JRC, 2012).

FAO assigns the area to the warm tropics with annual mean temperatures above 20° C (FAO and IIASA, 2014). The minimum temperature is about 23° C in July and the maximum temperature is 31° C in February (Alvarez et al., 2012). The length of the growing period for upland crops is indicated to be 180-209 days (FAO and IIASA, 2014). At the regional level, the site belongs to the agroecological zone E3 “Eastern Plateau and Mountain Blocks” in Tanzania (de Pauw, 1984) and is allocated to the moisture zone DM3 with two growing periods per year. The Usambara Mountains affect rainfall in the area with decreasing rainfall amounts at increasing distance from the mountain scarp (Agrar- und Hydrotechnik GmbH, 1976c). The average annual rainfall is 1074 mm (39-years average Korogwe town). The rainfall pattern follows a bimodal distribution with two rainfall seasons; the long rains between March and May, and the short rains between October and January (Agrar- und Hydrotechnik GmbH, 1976c).

Agriculture is the dominant economic activity in the region (Mwita et al., 2013). The 2007/2008 National Agricultural Census states that Korogwe was the district with the largest area planted with paddy rice in the Tanga region and the second largest area under irrigation (United Republic of Tanzania, 2012). Due to the closeness to the Arusha-Dar es Salaam highway, market access is good. The Malinda wetland began being used for agricultural production in the 1980s. Since then, the area under agriculture has increased and the wetland is still undergoing land use and land cover changes (Mwita, 2010). Seasonality in the observed anthropogenic influence has been described in detail by Kuria et al. (2014) using remote sensing data.

In the Malinda plains, cropland is the dominant land use category as well (Mwita, 2013), whereby monocropping, mixed cropping, and sequential cropping are all practiced with a wide range of agricultural crops. The central floodplain is used for rainfed rice cultivation during the wet season, whereby direct seeding is commonly applied. Irrigated rice is cultivated where water is available and transplanting of seedlings is commonly practiced. Maize and diverse vegetables are grown on the wetland fringe areas and on lower slopes. "Slash and burn" practices and fallow rotation systems are common, even in the wetland.

According to Sakané et al. (2013), the agricultural production system prevailing in the wetland can be characterized as "Mixed crop-non-dairy-based production". A widely distributed farm type is the "upland food crop - wetland paddy rice" type. Major parts of the wetland constitute public/communal land which is used for grazing (nomadic herding), especially during dry season (Mwita, 2013). Fishing with baskets and by construction of channel networks is a common activity as the flood waters recede. In areas with permanent flooding or at least soil saturation, papyrus and typha dominate the natural vegetation, while the seasonally flooded grazing lands are dominated by *Pennisetum mezianum-Sporobolus pyramidalis* communities, with frequent occurrences of *Cynodon dactylon* (Alvarez et al., 2012).

5.3.2 Sampling design

Five major categories or wetland sub-units have been defined to cover representative land use and land cover categories in the floodplain, including the major landscape positions and water sources (Table 5.1). These comprise 1) natural vegetation (NAT), 2) dry season grazing (GZ), 3) rainfed lowland rice during wet season and vegetables during dry season (RCS), 4) irrigated lowland rice with occasional vegetable cultivation (VEG) and 5) upland crops (UP).

5.3.3 Hydrometeorological monitoring

We monitored hydrometeorological state variables over a period of 26 months (March 2009 to April 2011). However, data gaps in the time series were common due to the malfunctioning of measurement devices, the need to abandon the sites and their inaccessibility during flooding.

Table 5.1: Representative sub-units of the floodplain, Tanzania, selected for hydrological monitoring. LULC=Land use/land cover

Code	**LULC**	**Landscape position**	**Moisture or flooding regime**	**Locality** (Figure 5.1)
NAT	Largely unused sites with natural vegetation (*Cyperus papyrus*, *Typha domingensis*)	Floodplain and swamps in depressions	Permanent or seasonal flooding / soil saturation, spillway from Mkomazi River, springs	Sangei basin, Kwasunga A ('Mkundi')
GZ	Dry season grazing; *Pennisetum mezianum-Sporobolus pyramidalis* communities	Floodplain	Seasonally flooded by ponding of rainwater and by Mkomazi River and tributaries	Majengo, Mafuleta, Kiloza, Kwasunga
RCS	Rainfed lowland rice during wet season and vegetables during dry season	Floodplain	Seasonally flooded by ponding of rainwater and by Mkomazi River and tributaries	Majengo, Mafuleta
VEG	Irrigated lowland rice with occasional vegetable cultivation	Fringe areas with springs	Seasonally high groundwater table	Kwasunga A ('Mkundi')
UP	Maize during dry season	Fringe areas and footslopes	Rarely flooded by runoff or ponding of rainwater	not specific

Meteorological variables

Precipitation was measured daily at 9 a.m. using a Hellmann rain gauge according to WMO standard (WMO, 2008). Relative humidity and temperature were monitored with a data logger (TGU-4500 Tinytag Ultra 2 Internal Temp/RH). A fully automatic weather station, capturing rainfall, temperature, wind speed and direction, relative humidity and solar radiation, as well as topsoil temperature, was only available starting at the end of 2010.

Groundwater level and flooding depth

The wetland was instrumented with 17 perforated piezometer pipes for monitoring the groundwater levels (Figure B.6(a)). The 2 m pipes were perforated at the lower tip over a length of 30 cm. In heavy clay soils, water table measurements by piezometers are better suited than shallow, unlined boreholes (Bouma et al., 1980). Last-mentioned bear the risk of water flowing through large continuous voids, thus erroneously suggesting the presence of shallow groundwater tables. However, such voids may also develop along piezometers if the space between the surrounding soil and the pipe has not been fully filled up during installation or if preferential paths have developed during the operation period. During periods of flooding, the depth of the water at the monitoring site was captured.

Soil moisture monitoring

Sixty locations within the wetland were monitored for volumetric soil moisture content to cover the diversity of the five sub-units (Figure B.6(a)). Moisture measurements were conducted every two days. We used the Frequency Domain Reflectometry (FDR) system PR2 by Delta-T Devices Ltd., Cambridge, UK (Delta-T Devices Ltd, 2008). The profile probe is a portable device which takes simultaneous measurements at the depths of 10, 20, 30, and 40 cm within an access tube. We assumed that the rooting zone of most crops cultivated in the floodplain does not exceed 50 cm due to clayey soils and the occurrence of hardpans. Three sensor readings were taken at each depth and the probe was rotated 120° between the readings. To test for correlation among the time series of soil moisture from different sites, we averaged the values from the measurement depths and calculated the 10-day average volumetric moisture content θ based on this data.

The general concept of moisture content measurement with the profile probe and the procedure of field calibration is described in Böhme et al. (2013). We applied the gravimetric method for sensor calibration. Gravimetric moisture content θ_G was converted to volumetric moisture content θ using bulk density (Eq. 5.1). Three sampling campaigns were carried out in the course of the study period. The first campaign was conducted between 13/2/2010-18/2/2010, the second between 13/12/2010-15/12/2010 and the third between 6/5/2011-11/5/2011.

$$\theta = \theta_G \times \frac{\rho_S}{\rho_W} \tag{5.1}$$

ρ_W is the density of water (=1 g/cm^3), and ρ_S is the bulk density of soil [g/cm^3].

5.3.4 Vegetation cover, soil physical and chemical properties

Information on the type of ground cover/crop development was recorded during the monitoring period. Soil physical and chemical properties were determined on soil samples collected in five, 2-meter-deep pits distributed over the study area (Figure B.6(b)). The procedure of soil description and classification followed FAO guidelines (FAO, 2006; FAO and ISRIC, 1990).

Infiltration rate and saturated hydraulic conductivity

The infiltration rate f was determined at 27 sites using the double-ring method (set with diameters of 28/53 cm). Prevailing land use categories and biophysical settings were represented (Figure B.6). A Compact Constant Head Permeameter (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) was applied measuring K_s in an auger hole down to approximately 200 cm below the soil surface. No measurements were conducted for the topsoil because this layer was to thin. Details for both methods are provided in Chapter 1.2.3.

Soil texture, bulk density, moisture retention curves, pH, organic carbon

Soil texture was analysed applying the hydrometer method on samples from the distinguished soil horizons in the profile pits and from the topsoil (0-20 cm) and subsoil (20-40 cm) at sites with infiltration experiments. Content in organic carbon for the same depths was measured by the wet oxidation method (Møberg, 2001). The pH was determined in a soil-water-suspension of 1:2.5. The analyses were conducted at the Department of Soil Science, Sokoine University of Agriculture, Tanzania.

Bulk density was determined with the core method using the same samples as for the calibration of the profile probe. Soil water retention curves were gained in pressure chambers with ceramic plates (Hinga et al., 1980) at Mlingano Agricultural Research Institute, Tanzania.
Alternatively, for a few samples, the HYPROP©-system (UMS GmbH, 2009) served the same purpose. Analyses were conducted at the Department of Soil Science, Sokoine University of Agriculture, Morogoro, Tanzania and at the Institute of Landscape Hydrology at the Leibniz Centre for Agricultural Landscape Research (ZALF) e.V., Müncheberg, Germany. The device determines the hydraulic conductivity function in addition to the water-retention curve. It applies the evaporation method according to Schindler (1980) in 250 cm^3 soil sampling rings.

5.3.5 Model description HYDRUS-1D

We used the Windows-based, one-dimensional HYDRUS-1D computer software package to model the water flow in porous media (Šimůnek et al., 2008). The model numerically solves the Richards equation (Radcliffe and Šimůnek, 2010).

$$\frac{\delta\theta(h)}{\delta t} = \frac{\delta}{\delta z}\left[K(h)\frac{\delta h}{\delta z} + K(h)\right] - S(h) \tag{5.2}$$

where θ is the volumetric water content [dimension L^3L^{-3}], t is time [T], z is the vertical coordinate axis [L] (positive upward), *K(h)* is the hydraulic conductivity, h is the water pressure head [L] and *S(h)* is a water sink term [$L^3L^{-3}T^{-1}$]. Unsaturated soil hydraulic properties were described with the van Genuchten-Mualem equation (Mualem, 1976 and van Genuchten, 1980 in Wang et al., 2014) where

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1+|\alpha h|^n]^m} & \text{for } h < 0 \\ \theta_s & \text{for } h \geq 0. \end{cases} \tag{5.3}$$

and

$$K(h) = K_s {S_e}^l \left[1 - \left(1 - {S_e}^{\frac{1}{m}}\right)^m\right]^2 \tag{5.4}$$

where the effective soil water saturation S_e [-] is

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{5.5}$$

$$m = 1 - \frac{1}{n} \quad n > 1 \tag{5.6}$$

θ_r is the residual water content [L^3L^{-3}], θ_s is the saturated water content [L^3L^{-3}]. α [L^{-1}], n [-], and *l* [-] are fitting parameters. α is related to the air-entry value, n is a pore-size distribution index and *l* is a tortuosity parameter in the conductivity function [-] which is mostly set to 0.5.

We chose the van Genuchten-Mualem model as it yielded high R^2 (>0.9) for the fitting of retention curves in RETC (explanation follows) (van Genuchten et al., 1991) and in the HYPROP© data evaluation software (Schindler et al., 2011) (Chapter 5.3.4). An air-entry value of -2 cm was fixed as has been recommended by Radcliffe and Šimůnek (2010) for applications involving soils with high contents of clay size fraction.

The HYDRUS-1D code is coupled with the ROSETTA computer program (Schaap et al., 2001). ROSETTA uses pedotransfer functions to predict van Genuchten water retention parameters (van Genuchten, 1980) and saturated hydraulic conductivity K_s from soil textural class information, the soil textural distribution, bulk density and one or two water retention points as input. One should be cautious when applying ROSETTA on soils with proportions of clay size fraction $>$60%. The program's sample pool for parameter estimation is comparably small for this soil texture class (Schaap et al., 2001).

For sites with measured moisture retention curves, the RETC program (van Genuchten et al., 1991) was used to predict the soil water retention function of unsaturated soils (Chapter 5.3.4). The nonlinear least-squares parameter optimization method is used for estimating the unknown coefficients in the hydraulic models. For samples which were analysed using the HYPROP©-system (Chapter 5.3.4), the HYPROP© data evaluation software was used to fit the data to the van Genuchten-Mualem model (Schindler et al., 2011).

We chose one representative site for each sub-unit to calibrate and validate the HYDRUS-1D soil water model using time series of soil moisture measurements.

Soil material layers in the model were defined according to soil horizons distinguished in the soil pits. However, in some cases, we saw it necessary to introduce additional material layers into the model to describe the observed soil moisture measurements at 10, 20, 30 and 40 cm in more detail.

For soil material layers for which time series of volumetric soil moisture measurements were available, we determined the hydraulic parameters to describe the soil retention and unsaturated hydraulic conductivity functions through inverse modelling. An objective function, expressing the deviations between predicted volumetric soil water content from a numerical solution of the flow equation and measured soil water content at different depths and times is minimized through the application of a Marquardt-Levenberg type parameter optimization algorithm included in HYDRUS-1D (Šimůnek et al., 2013). The aim of this procedure is to determine the best estimate of the hydraulic model parameters (Radcliffe and Šimůnek, 2010). Soil hydraulic parameters derived from measured retention curves were used as initial values which were then iteratively improved during the procedure until a desired precision was achieved. For the remaining material layers, estimates of hydraulic parameters from ROSETTA were used.

Information on the defined upper and lower model boundary conditions are summarized in Table A.4. Potential evapotranspiration ET_p constituted the upper model boundary ("atmospheric boundary condition"). For those sites where flooding was encountered, we allowed the model to build up a surface layer of a defined depth ("atmospheric boundary condition with surface layer").

ET_p was calculated using Hargreaves equation (Jensen et al., 1997) as it is implemented in HYDRUS-1D (Šimůnek et al., 2008). It uses daily data on minimum and maximum temperature (Eq. 5.7).

$$ET_p = 0.0023 \times R_a \times (T_m + 17.8) \times \sqrt{T_R} \tag{5.7}$$

whereby R_a is the extra-terrestrial radiation in the same units as ET_p, T_m is the daily mean air temperature, computed as an average of the maximum and minimum air temperatures [° C], T_R is the temperature range between the mean daily maximum and minimum air temperatures [° C].

For sites with a shallow groundwater table with less than 2 m distance from the soil surface, a variable pressure head was used as the lower model boundary. When the water table dropped below the measurement depth of the piezometer (200 cm), we used estimates of the water table depth to define the lower model boundary. We were not able to explain abrupt drops and rises in groundwater tables observed for a few piezometers. In order to describe the dynamics of the groundwater table for such cases, we used individual viable data of groundwater table measurements together with soil moisture data at a 40 cm depth (indicating soil saturation close to soil surface).

5.4 Results

5.4.1 Site specific variability of soil properties

Soils in the floodplain are generally deep to very deep, with a soil depth of more than 200 cm. Major parts of the area, represented by profile pits 1 and 2 (soil-physical and soil-chemical parameters in Table 5.2, location of pits in Figure B.6(b)), were assigned to the FAO reference soil group "Stagnic Vertisols (ferric, pellic)".

Pit 1 is located in an area used for the cultivation of rainfed lowland rice during wet season and vegetables during dry season (RCS) (descriptions of categories in Table 5.1). Pit 2 is under dry season grazing (GZ). Both locations are practically flat with slopes less than 1%. Furthermore, the area is annually flooded by the Mkomazi River and its tributaries for about 30-90 days/yr, during and after the rainy seasons. The low permeability of the upper soil layer supports the ponding of rainwater. Extensive periods of soil saturation are indicated by a high abundance of mottles and iron and manganese nodules. The groundwater level during the dry season is mostly below 2 m.
In pit 1, the increase in the proportion of the sand size fraction with depth is accompanied by a decrease in the proportion of the clay size fraction. Thus, a transition from texture class clay at the soil surface to loamy sand at 2 m depth has been described. Modified surfaces, where the outer, finely textured part is greyish and the interior has a yellowish sandy matrix, are an outstanding feature of the second horizon (Table 5.2). The clay size fraction dominates throughout profile 2. Cracking and the occurrence of slickensides as a consequence of swell-and-shrink behaviour are commonly encountered in clay-rich horizons at both sites.

Profile pit 3 is located at the western fringe of the floodplain, which is used for cultivation of maize (MZ) (Figure B.6(b)). The site slopes slightly eastward. The dark reddish brown soils at this site were assigned to the group of "Ferralic Nitisol (rhodic)". They experience severe shrinking and swelling due to high proportions of the clay size fraction. Groundwater is below 2 m and flooding occurs rarely.

A black to dark (grayish) brown "Gleysol" was encountered in pits 4 and 5, where the groundwater table seasonally rises to less than 200 cm below the soil surface. In pit 5, it can even reach 50 cm below the surface due to the activation of springs during the rainy season (Figure 5.1). Frequent wetting and drying cycles are indicated by the abundance of mottles and iron and manganese nodules. Pit 4 is located in a nearly level, seasonally flooded area with reeds and cyperaeae, partially used for dry-season grazing.

The very gently sloping surroundings of pit 5 are commonly utilized for the cultivation of irrigated rice and vegetables, thus representing the class VEG (Table 5.1). The common texture class in pit 4 is clay with 50 to 60 percent of the clay size fraction and in pit 5 it is a sandy clay with about 40 percent of the clay size fraction. At site 4, a thin salt crust was encountered. Mollic properties are well expressed in the Gleysol of pit 5.

Table 5.2: Physico-chemical soil parameters in five sub-units of the floodplain, Tanzania. ρ_S=bulk density, OC=Organic Carbon, K_s=saturated hydraulic conductivity from Constant Head Permeameter (average over three measurements unless stated otherwise), s=Standard deviation, NAT=natural vegetation, GZ=dry season grazing, RCS=Rainfed lowland rice during wet season and vegetables during dry season, VEG=Irrigated lowland rice with occasional vegetable cultivation, UP=upland crops, n.d.=not determined, *samples from nearby sites contained 2.3-2.6% OC, $\ll$=layer to thin for measurement, GW=no measurement because of shallow groundwater table

Horizon	Depth	Clay	Silt	Sand	ρ_S	pH(water)	OC	$K_s \pm s$
	cm		%		g/cm^3		%	cm/d
RCS-pit1								
1	0-10	55	19	26	0.95	6.0	n.d.*	$\ll$
2	10-68	47	9	44	1.62	6.6	0.59	4.3±0.1
3	68-130	33	5	62	1.91	7.8	0.20	1.3; 19.5
4	130-200	17	1	82	1.38	7.8	0.14	120.7±49.2
GZ-pit2								
1	0-13	59	11	30	1.62	5.3	2.73	$\ll$
2	13-65	69	9	22	1.74	6.0	0.98	n.d.
3	65-130	77	3	20	1.66	7.7	0.74	n.d.
4	130-200	69	3	28	1.74	8.2	0.10	n.d.
UP-pit3								
1	0-20	41	17	42	1.46	7.5	2.77	$\ll$
2	20-65	49	17	34	1.49	6.9	1.56	21.4
3	65-130	51	7	42	1.72	7.7	0.39	n.d.
4	130-150	51	13	36	1.89	6.1	1.17	1.6±0.7
5	150-170	51	3	46	1.86	8.7	0.25	1.0±0.9
NAT-pit4								
1	0-10	53	17	30	0.87	5.9	6.32	$\ll$
2	10-70	57	7	36	n.d.	7.7	0.29	8.6±1.9
3	70-135	63	5	32	n.d.	8.0	0.20	0.6±0.7
4	135-200	51	7	42	1.59	7.8	0.27	1.6±1.0
VEG-pit5								
1	0-20	31	11	58	1.37	7.8	2.69	$\ll$
2	20-65	39	11	50	1.58	8.3	0.89	19.3±9.7
3	65-90	43	9	48	1.66	8.3	0.59	GW
4	90-120	41	7	52	1.71	8.4	0.39	GW
5	120-145	35	7	58	1.76	8.2	0.23	GW
6	145-200	39	5	56	n.d.	8.2	0.35	GW

Infiltration rates from double-ring infiltrometer

Infiltration rates from the 27 infiltration experiments conducted in all types of land use/land cover (Figure B.6(b)) ranged from 0.5 to 26.5 cm/h, with an average of 7 cm/h (Figure 5.2). The lowest values were recorded in grazing areas, although the occurrence of cracks in heavy clay soils impeded the infiltration experiments.

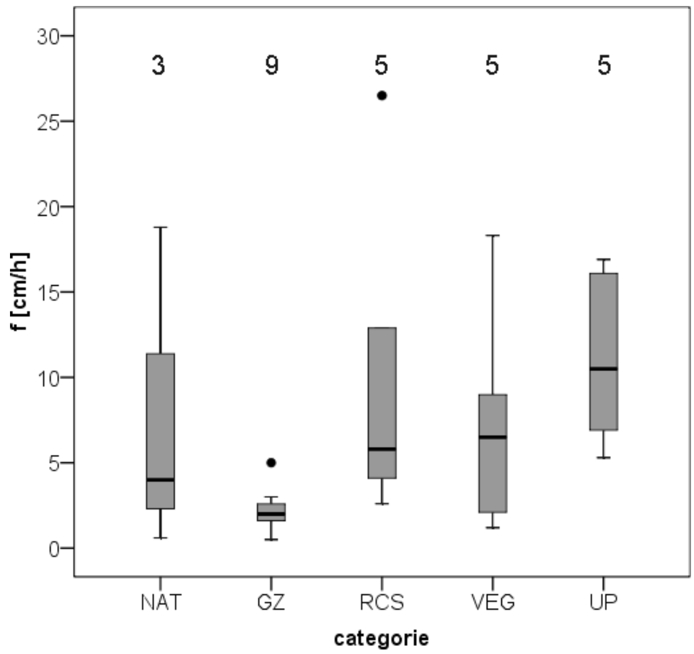


Figure 5.2: Box-and-Whisker plot of infiltration rate f as derived from double-ring experiments. Floodplain, Tanzania. NAT=natural vegetation, GZ=dry season grazing, RCS=Rainfed lowland rice during wet season and vegetables during dry season, VEG=Irrigated lowland rice with occasional vegetable cultivation, UP=upland crops. Number above each box indicates sample size n. Outliers are illustrated as a dot. They are outside the inner fence of the boxplot, i.e. the first quartile minus 1.5 times the interquartile range (IQR), or the third quartile plus 1.5 times IQR.

A one-way Welch ANOVA was realized to determine if the infiltration rates differed among the various types of LULC. Data was normally distributed for each group, as assessed by the Shapiro-Wilk test (p>0.05). The two outliers in the boxplot were excluded from further analysis. We found heterogeneity of variances, as assessed by Levene's test of homogeneity of variances (p=0.009). The differences among the groups was not statistically significant, Welch's F(4,6.588)=3.899, p=0.061.

Furthermore, there was no statistically significant correlation between infiltration rates and bulk density, or texture of the topsoil and subsoil, respectively.

5.4.2 Calibration of capacitance sensor

We used 155 samples, each in 3 replicates and from 33 sites, to calibrate the FDR moisture sensor (Table A.1). No samples for grazing areas were included due to the disturbance of sites. The relative variability of the three replicates, expressed through the coefficient of variation (CV), was small: The CV was less than 0.2 both for gravimetric moisture measurements and FDR millivolt output. Only nine samples were eliminated as outliers with respect to bulk density, gravimetric water content and volumetric water content (calculated based on gravimetric water content). After confirming the normality of the data distribution, a paired-samples t-test revealed statistically significant differences of volumetric moisture content (gravimetric method) between the first and second campaign, as well as between the first and third campaign (Table 5.3).

Table 5.3: Paired-samples t-test applied on mean volumetric moisture content θ obtained gravimetrically at three sampling dates in the floodplain, Tanzania. Mean and standard deviation for the same campaign may differ among pairs as not all sites were sampled in all three campaigns. Bold numbers designate statistically significant difference in θ between sampling dates at 5% level. t=t-value, df=degrees of freedom, nd=normal distribution with p-value of Shapiro-Wilks test. In case of violation of normal distribution assumption significance of difference was confirmed with Wilcoxon signed-rank test.

Campaign	**Mean** m^3/m^3	**Standard deviation** m^3/m^3	**Sample size *n***	***t*(df)**	***p*-value**	**nd**
1	0.261	0.131	29	$t(28)$=-3.310	**0.003**	0.806
2	0.343	0.960				
1	0.278	0.118	25	$t(24)$=-5.978	<**0.0005**	0.144
3	0.395	0.884				
3	0.394	0.886	25	$t(24)$=1.589	0.125	0.148
2	0.362	0.111				

The mean moisture content in February 2010 (campaign 1) was 0.08 m^3/m^3 lower than in December 2010 (campaign 2) (95% confidence interval, 0.03 to 0.13 m^3/m^3). As well, it was, on average, 0.12 m^3/m^3 lower than in May 2011 (campaign 3) (95% confidence interval, 0.08 to 0.16 m^3/m^3). Generally, the upper 10 cm showed a higher variation of moisture contents than the bottom soil.

In total, volumetric moisture contents θ, determined using the gravimetric method, ranged from 0.06 to 0.62 m^3/m^3 (Figure 5.3), with a mean of 0.34 m^3/m^3. The data was normally distributed according to Q-Q plot and Shapiro-Wilk test (p=0.087, α=0.05).

The application of the calibration functions provided by the manufacturer ("default calibration") for mineral and organic soils overestimates moisture contents in most cases (Figure 5.4). However, it is hardly possible to identify a clear trend across the measurement range.

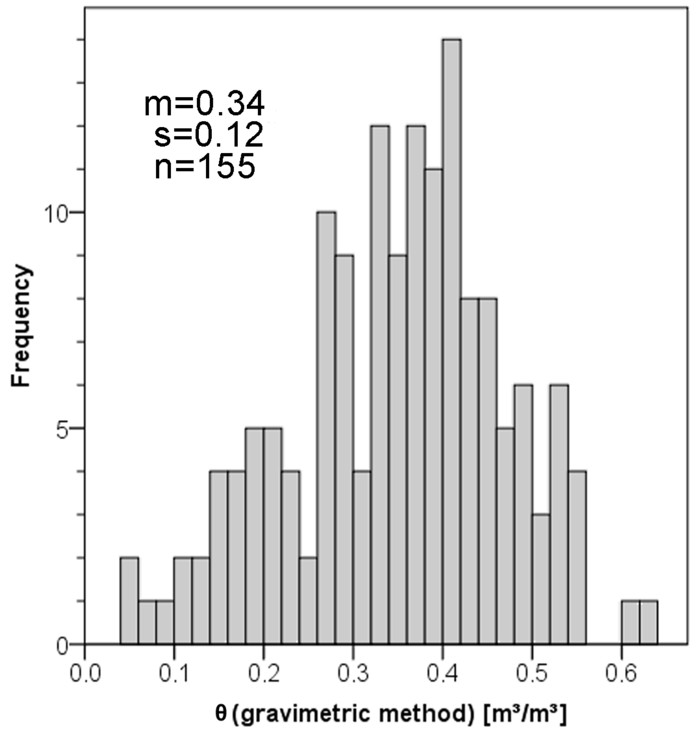


Figure 5.3: Frequency distribution of volumetric moisture contents θ (gravimetric method) from three sampling campaigns in the Malinda floodplain, Tanzania; class size 0.02 m^3/m^3. m=mean of θ, s=standard deviation of θ, n=sample size.

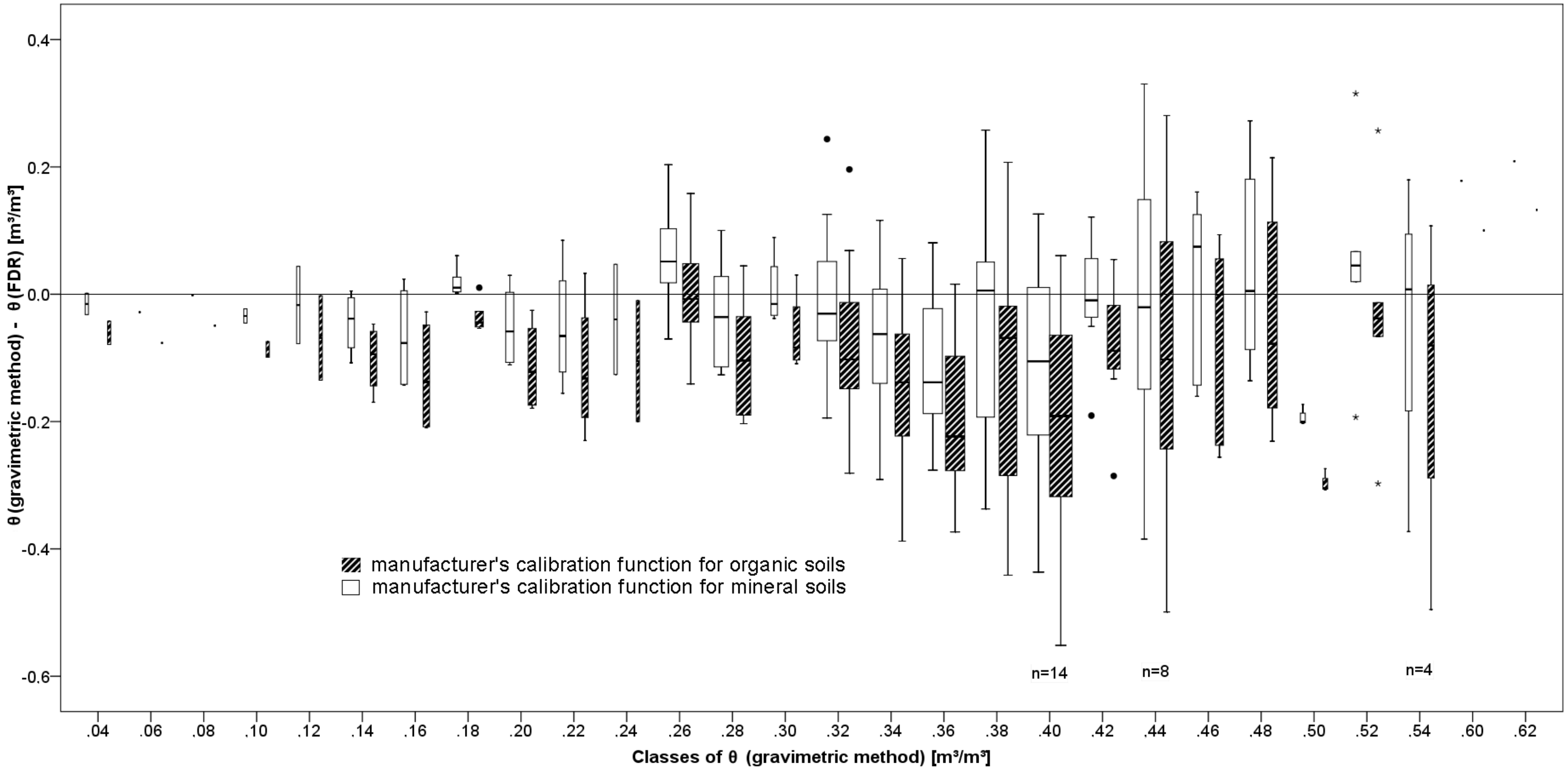


Figure 5.4: Box-and-Whisker plot of differences between volumetric moisture contents θ (gravimetric method) and FDR-based volumetric moisture contents θ (FDR) for the floodplain, Tanzania. Manufacturer's calibration functions for mineral and organic soils were used for the conversion of FDR millivolt output into volumetric moisture contents. Differences averaged for classes of volumetric moisture contents θ (gravimetric method); class size 0.02 m^3/m^3. Width of bars represents sample size n. Outliers are illustrated as a dot. They are outside the inner fence of the boxplot, i.e. the first quartile minus 1.5 times the interquartile range (IQR), or the third quartile plus 1.5 times IQR. Extreme outliers are illustrated as an asterisk (*). They are outside the outer fence of the boxplot, i.e. the first quartile minus three times IQR, or the third quartile plus three times IQR.

Linear regression relationships between volumetric water content θ (gravimetric method) and the square root of the soil bulk electrical permittivity $\sqrt{\epsilon}$ must be established to predict volumetric moisture contents from the millivolt output of the profile probe. Figure 5.5 demonstrates that the linear relationship between θ (gravimetric method) and $\sqrt{\epsilon}$ is depth-specific for the floodplain soil samples. Data points for a depth of 10 cm ("topsoil") are distinct from data points for depths of 20, 30 and 40 cm. Therefore, we combined these into one entity ("bottom soil") and established depth and site-specific linear regression equations (Table A.2).

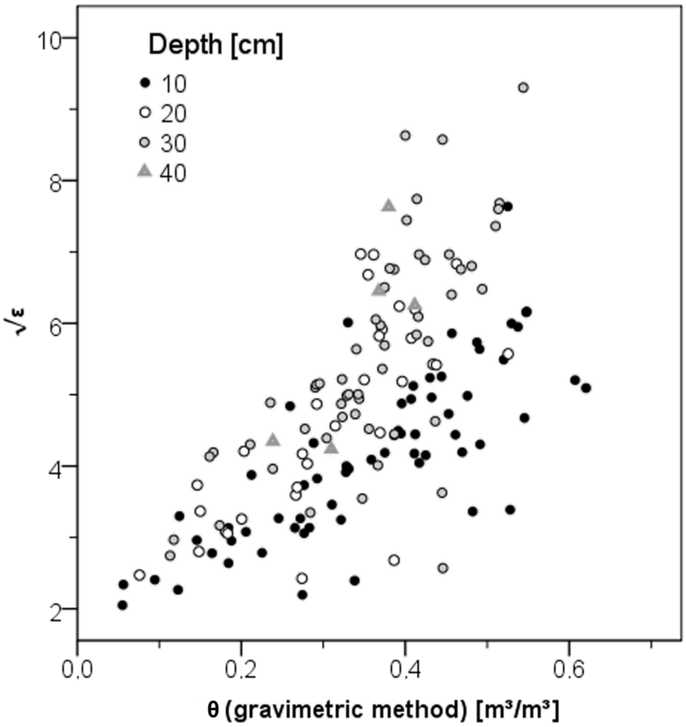


Figure 5.5: Readings of square root of soil bulk electrical permittivity $\sqrt{\epsilon}$ against θ (gravimetric method). Floodplain, Tanzania. $\sqrt{\epsilon}$ calculated from profile probe millivolt output. Sampling depths are color-coded.

An upper limit of the probe output signal was fixed at 980 mV which corresponds to saturated conditions (Böhme et al., 2013) (Figure 5.6). Measurements with more than 980 mV were excluded from the linear regression analysis.

The coefficient of determination R^2 of linear regression analysis was higher for topsoil samples than for bottom soil samples. The derived relationships were significant for all subsets, except for natural vegetation (NAT) which was represented by only a few samples (Table A.1). Considering the high contents of organic carbon in the topsoil of natural vegetation (Table 5.2), we used the manufacturer's calibration for organic soils at the respective sites.

Accordingly, the volumetric soil moisture θ can be predicted from the square root of the soil bulk electrical permittivity ϵ (Delta-T Devices Ltd, 2008):

$$\sqrt{\epsilon} = a_0 + a_1 \times \theta \tag{5.8}$$

with a_0 of 1.3 and a_1 of 7.7 for organic soils. For 20 to 40 cm depth measurements at these sites we used the default calibration function for mineral soils with a_0 of 1.6 and a_1 of 8.4.

The best goodness-of-fit (R^2) was obtained for the data set which comprised all topsoil samples and that data set which comprised all bottom soil samples, exclusive NAT-samples (R^2>0.6 m^3/m^3, Table A.2). For the topsoil, linear regression yielded an a_0 of 1.609 and an a_1 of 7.186. For bottom soil, we used coefficients a_0 to 2.090 and a_1 to 8.354 to translate the profile probe millivolt output into volumetric moisture content.

The root mean squared error (*RMSE*) of FDR-based moisture contents using the new conversion functions (excluding sites NAT and probe output >980 mV) was 0.09 m^3/m^3 for a 10 cm depth and 0.10 m^3/m^3 for a depth of 20 to 40 cm (Figure 5.7). The root mean squared difference (*RMSD*) as a measure of the default calibration accuracy was 0.10 m^3/m^3 / 0.09 m^3/m^3 for topsoil (manufacturer's calibration equation for mineral/organic soil) and 0.11 m^3/m^3 / 0.150 m^3/m^3 for bottom soil (mineral/organic soil).

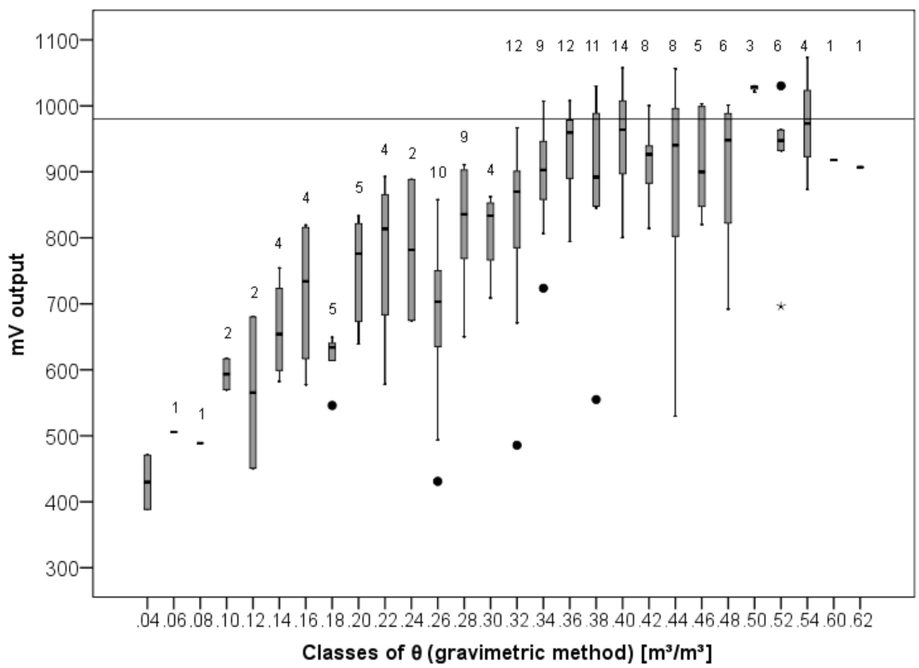
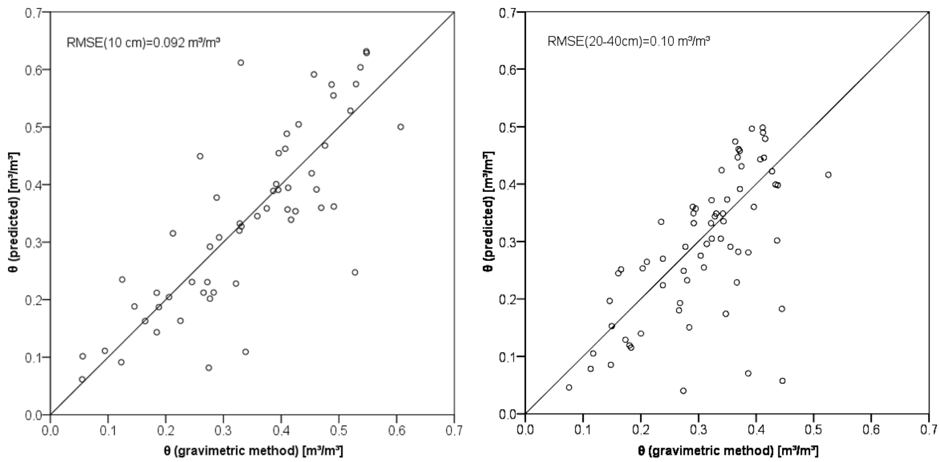


Figure 5.6: Box-and-Whisker plot of millivolt output of FDR profile probe for the floodplain, Tanzania. Labels at x-axis are classes of volumetric moisture contents θ (gravimetric method); class size 0.02 m^3/m^3. Horizontal line indicates set boundary for saturated soil conditions (after Böhme et al., 2013). Number above each box indicates sample size *n*. Outliers are illustrated as a dot. They are outside the inner fence of the boxplot, i.e. the first quartile minus 1.5 times the interquartile range (*IQR*), or the third quartile plus 1.5 times *IQR*. Extreme outliers are illustrated as an asterisk (*). They are outside the outer fence of the boxplot, i.e. the first quartile minus three times *IQR*, or the third quartile plus three times *IQR*.



(a) (b)

Figure 5.7: Scatter plot of FDR-based volumetric moisture contents θ predicted with new calibration function against volumetric moisture content θ (gravimetric method). Floodplain, Tanzania. The solid line shows the 1:1 ratio: (a) 10 cm depth, and; (b) 20 to 40 cm depth.

5.4.3 Temporal and spatial soil moisture dynamics

For four sites, the HYDRUS-1D soil water model was set up, calibrated and validated. Table A.4 summarizes the model parameters and boundary conditions. For most cases, the water retention curves created with the van Genuchten parameters from inverse model calibration deviate significantly from the measured retention curves (Figure 5.8(a)). An example for a better agreement is displayed for the site with irrigated lowland rice and occasional vegetable cultivation (VEG) (Figure 5.8(b)). Generally, the agreement between calibrated retention curves and HYPROP©-system output was better than between calibrated retention curves and retention curves gained in pressure chambers.

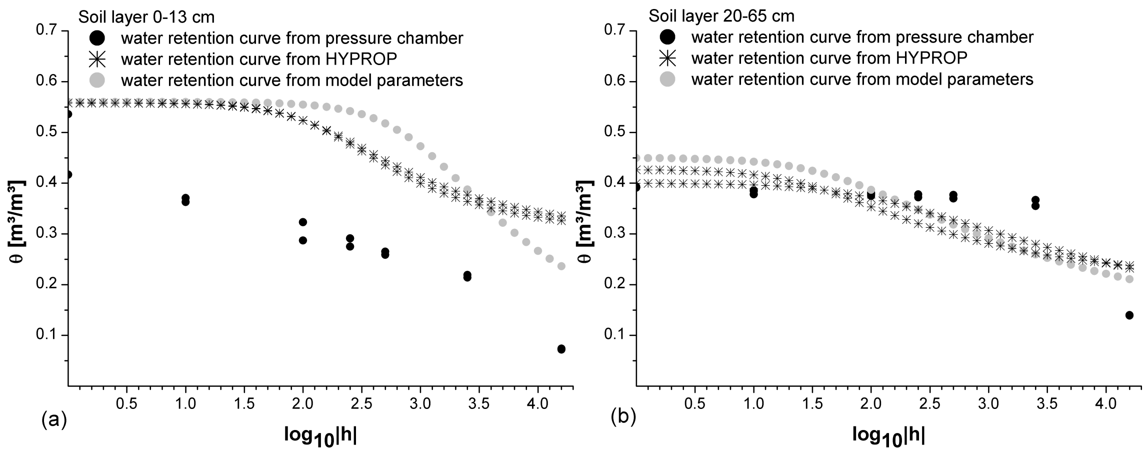


Figure 5.8: Comparison of measured retention curves with curves generated from model parameters for the floodplain, Tanzania; (a) GZ: Dry season grazing; (b) VEG: Irrigated lowland rice with occasional vegetable cultivation.

Natural vegetation

Sites with year-round high moisture levels and prolonged periods of flooding are characterized by natural vegetation such as *Cyperus papyrus*, *Typha domingensis* or *Typha capensis*. Soil-physical and chemical parameters from soil pit 4 are considered to be representative for this sub-unit of the floodplain (Table 5.2). Figure 5.9 exemplifies the time series for a site under *Typha domingensis*. From 2009 to 2010 the location was extensively flooded. For this reason, only few soil moisture measurements were carried out, which did not permit to set up and calibrate a soil water model with HYDRUS-1D. Remarkably, the moisture level dropped rapidly after the floods receded and after the short rains from November 2010 to January 2011.

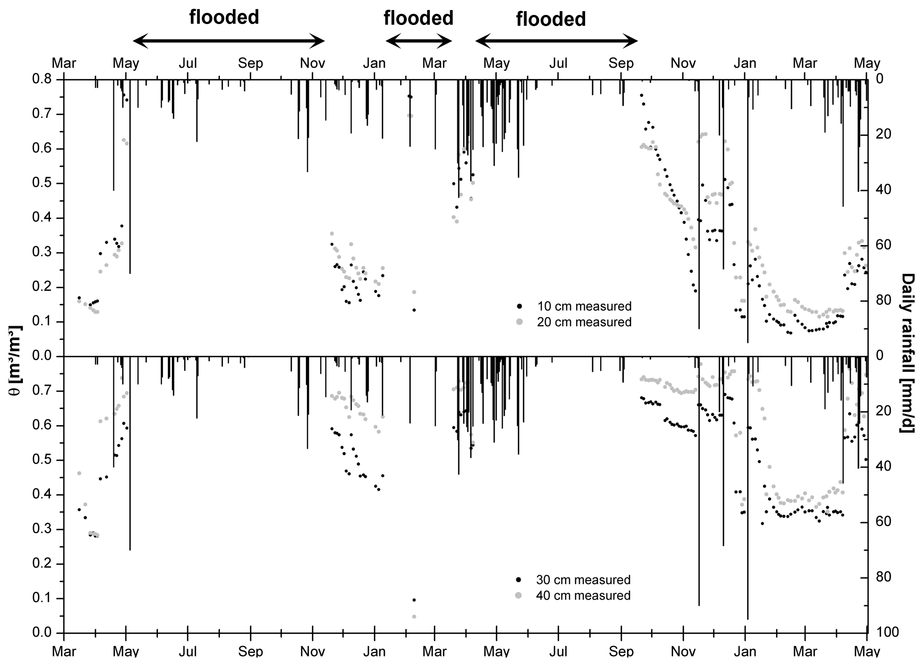


Figure 5.9: Natural vegetation (NAT), floodplain, Tanzania: Observed volumetric soil moisture contents θ at 10 to 40 cm depth at site MANVS2. Period 03/2009 to 05/2011. Location of MANVS2 is displayed in Figure B.6(a).

Dry season grazing

Soil-physical and chemical parameters from soil pit 2 (Table 5.2) are considered to be representative for dry season grazing sites MAGZS1 and MAGZS2 (Figure B.6(a)). The Mkomazi River passes the sites at about 300 and 420 m distance and floods the area regularly. During the observation period, the groundwater level was deeper than 2 m.

Cynodon dactylon is a common grass in the grazing areas. In clayey soils it has a rooting depth of about 40 to 50 cm (Cook, 2005). For our case, most roots were observed in the upper 40 cm of the soil profile.

The status of the soil moisture was captured between early March and mid-July 2009 (4.5 months). What is most striking about the time series presented in Figure 5.10 is the rather large amplitude of soil moisture variation at a 30 cm depth when compared to a 10 cm depth. Both data sets share a very weak response to rainfall events in April and May 2009. The observation period was too short to be split into a model calibration and validation period. Furthermore, it was not possible to establish a reasonable correlation analysis between observed soil water contents at site MAGZS1 and neighbouring grazing sites due to the limited amount of measurements during the same period.

We tested three different approaches for determining soil hydraulic parameters for the HYDRUS-1D model calibration (Table A.4). These were: a) inverse modelling using observed soil moisture contents at 10 and 30 cm depths, b) ROSETTA neural network prediction using soil texture and bulk density as input and c) parameter fitting with the RETC software tool from the measured soil water retention curves (pressure chambers) and cross-checking with the results from HYPROP©-system. A comparison of model performance for the three approaches is displayed in Figure 5.10.

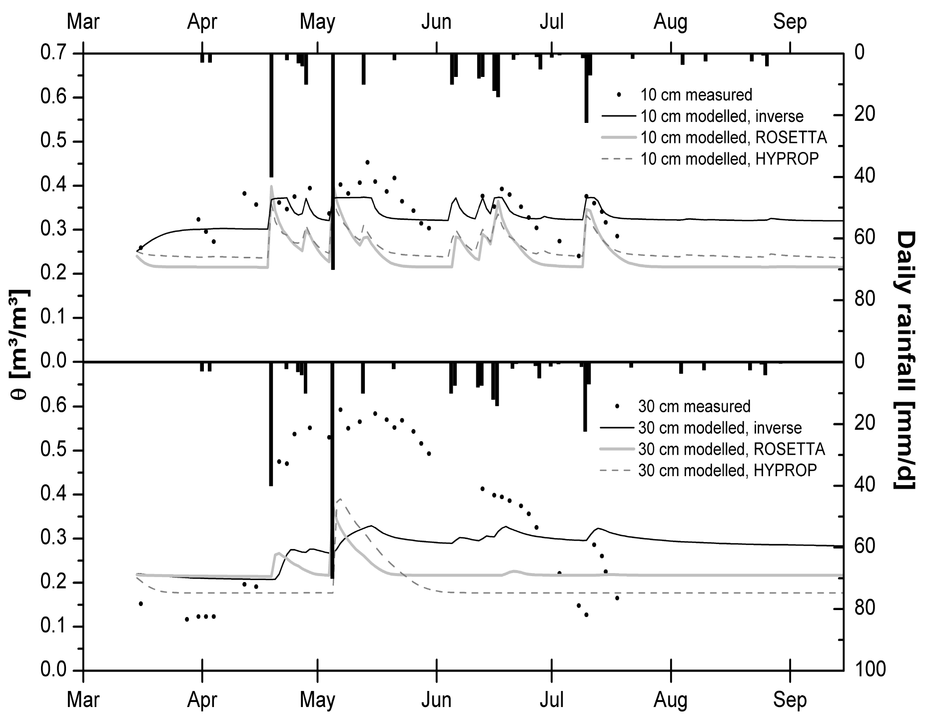


Figure 5.10: Dry season grazing (GZ), floodplain, Tanzania: Observed vs. modelled volumetric soil moisture contents θ at 10 and 30 cm depth at site MAGZS1. Monitoring period 03/2009 to 07/2009. Location is displayed in Figure B.6(a). Use of three different approaches for parameter estimation: inverse modeling, ROSETTA neural network prediction, measured water retention curves.

Quality measures of model performance are given in Table A.5. Root mean squared errors (*RMSE*) increase with depth for all three approaches of parameter estimation. Model performance is better for inverse modelling than for parameter fitting from measured retention curves and ROSETTA neural network's prediction. Altogether, *RMSE*, as well as Nash-Sutcliffe model efficiency coefficient (*NSE*) and R^2 indicate an unacceptable model performance for the grazing site, especially below a 10 cm depth ($RMSE>0.1$ m^3/m^3, $NSE<0$). For this reason, we did not calculate the soil water balance as it would yield unreliable results.

Rainfed lowland rice during wet season and vegetables during dry season

MARCS1-1, MARCS1-2 and MARCS1-3 represent sites with rainfed lowland rice during wet season and vegetables during dry season (RCS) (Figure B.6(a)). Farmers construct bunds around the rice fields to retain the flood and rain water from the long wet season. Direct seeding is commonly applied. Soil physical and chemical parameters were studied in detail in soil pit 1 (Table 5.2). MARCS1-1 is located about 20 m away from the other two sites, which are all in the same plot (Figure B.6(a)).

The correlation between the locations' soil water contents averaged over 10 days was high, with an R^2 above 0.9 (Figure 5.11).

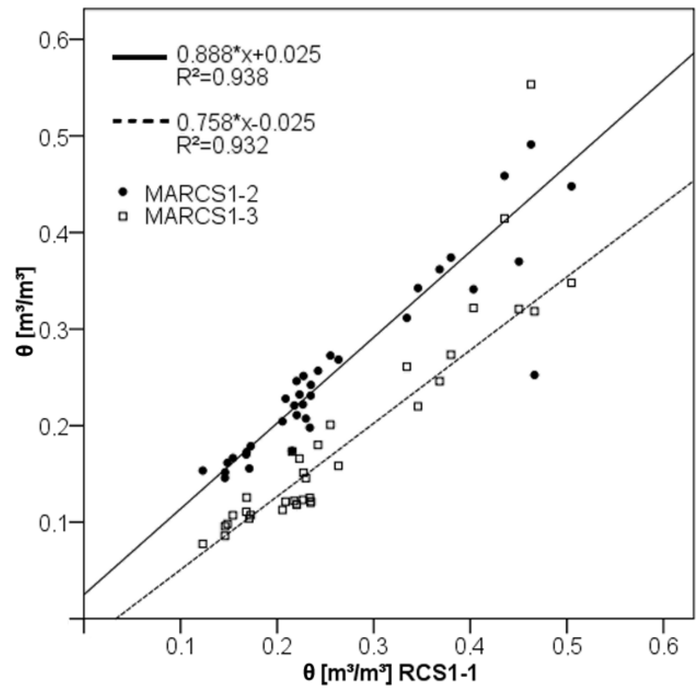


Figure 5.11: Scatter plot of observed soil water content θ at MARCS1-1 against those at two other rainfed rice sites (MARCS1-2, MARCS1-3). Floodplain, Tanzania. Averages over 10-20-30 cm depth and 10 days. Location of MARCS1-1 is displayed in Figure B.6(a).

During the monitoring period, the farmer did not grow vegetables after the floods receded and the ground was covered with weeds. As no growth parameters were available for weeds, we used Feddes' parameters for a constant cover with beans as implemented in HYDRUS-1D to facilitate modelling. For the period during which rice was cultivated, we used Feddes' parameters from Singh et al. (2003). Leaf area index (LAI) was set to 2.7 for the growing period (Tilahun-Tadesse et al., 2013) and the maximum rooting depth was set to 40 cm (Ladha et al., 1998).

Flooding was observed between 24/12/2009 and 22/02/2010 and again from 02/04/2010 to 09/06/2010. From March to early May 2009, the groundwater level in the adjacent piezometer was below 2 m (Figure 5.12). Up to mid-May 2009, a level rise to 1 m below soil surface was recorded as a consequence of intense rainfalls. Once again, groundwater level dropped at the end of June. Until December 2009, the water table remained below two meters. From January to August 2010, the water level in the piezometer came close to the soil surface. After an abrupt drop below 2 m, it remained at this level until the end of the campaign in May 2011.

In summary, the response of the topsoil (0-20 cm) to rainfall events can be well described by hydraulic parameters determined through inverse modelling. *RMSE* of the calibration period was 0.06-0.08 m^3/m^3 for the topsoil and 0.10-0.14 m^3/m^3 for the subsoil (20-40 cm) (Table A.5). *RMSE* of the validation period, integrated over all four depths (0.19 m^3/m^3), was nearly two times the *RMSE* of the calibration period (0.10 m^3/m^3). Figure 5.12 allows for a comparison of the model performance for the whole observation period, including the calibration and validation period, as well as additional periods containing data gaps. Thus, it is possible to close the data gap between August and October 2009 for the topsoil, but critical for the subsoil due to poor model performance. The assumption of the model's transferability to sites within the same plot (Figure 5.11) can be confirmed with Figure 5.13 and quality measures in Table A.5.

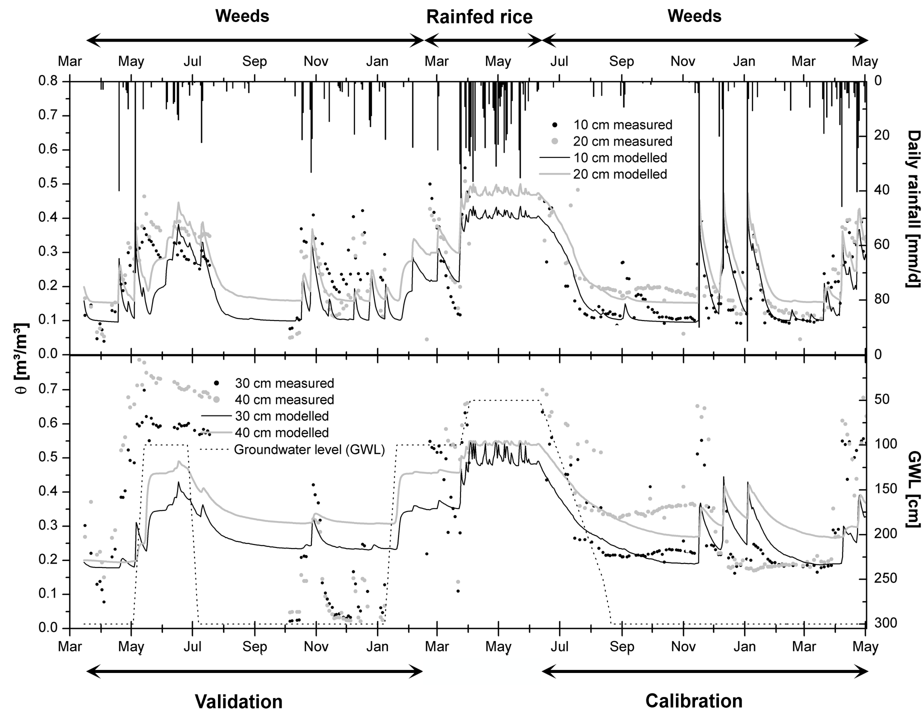


Figure 5.12: Rainfed lowland rice during wet season and vegetables during dry season (RCS), floodplain, Tanzania: Observed vs. modelled volumetric soil moisture contents θ at 10 to 40 cm depth at site MARCS1-1. Period 03/2009 to 05/2011. Location is displayed in Figure B.6(a). Site influenced by high groundwater table. Measurement depth of piezometer was 200 cm. For GWL>200 cm, estimates were used for modelling.

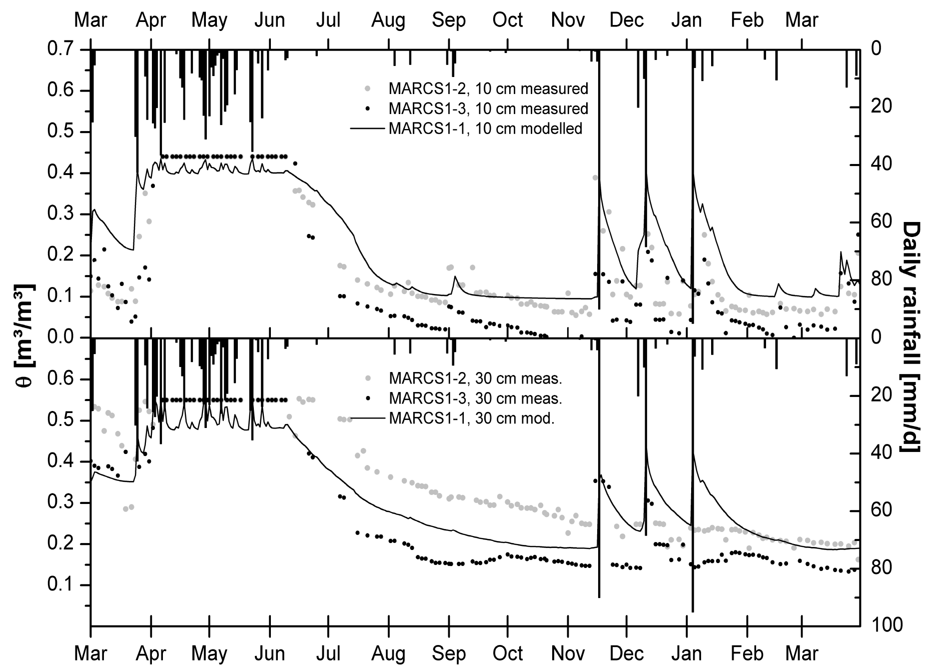
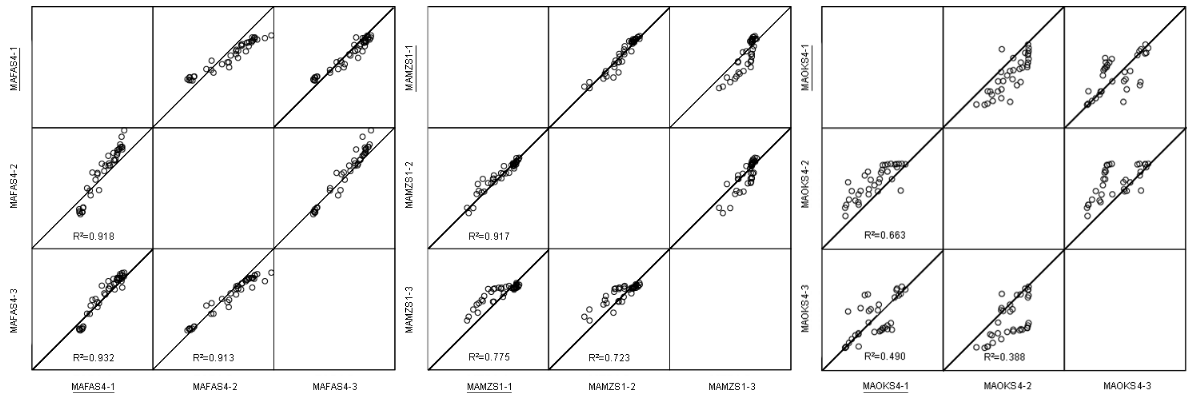


Figure 5.13: Rainfed lowland rice during wet season and vegetables during dry season (RCS), floodplain, Tanzania: Validation of model calibrated for MARCS1-1 against measured soil moisture contents θ at 10 and at 30 cm depth at neighbouring sites MARCS1-2 and MARCS1-3. Period 03/2010 to 04/2011.

Irrigated lowland rice with occasional vegetable cultivation

Three plots were selected as representatives for the cultivation of irrigated lowland rice and occasional vegetable cultivation such as okra. Each of the plots was equipped with three FDR access tubes placed 20 m apart from one another. The plots MAFAS4 and MAMZS1 (Figure B.6(a)) both have a soil texture of sandy clay with about 46 to 58 percent sand size fraction and 37 to 45 percent clay size fraction. MAOKS4 has a clay texture with 32 to 42 percent sand size fraction and 49 to 53 percent clay size fraction. The reader is referred to Table 5.2 for descriptions of the soil physical and chemical parameters of the nearby soil pit 5.

In a first attempt, we tested the *intra-plot* correlation among the time series of volumetric soil moisture content. The scatterplots in Figure 5.14 show linear relationships with the slopes of the regression equation close to 1 for all three plots comprising the three FDR tubes. This allowed us to carry out an *inter-site* linear regression analysis using only one FDR site from each plot. The selected sites are underlined in Figure 5.14.



(a) (b) (c)

Figure 5.14: Scatter plots of observed soil water contents θ from three plots with irrigated rice/vegetables cultivation, each comprising three FDR access tubes for moisture monitoring. Floodplain, Tanzania. The solid line shows the 1:1 ratio. MAOKS4 and MAMZS1 located about 200 m away from MAFAS4. FDR access tubes in each plot located at a 20 m distance from each other. Locations are displayed in Figure B.6(a). Averages over 10-20-30 cm depth and 10 days: (a) plot MAFAS4; (b) plot MAMZS1; (c) plot MAOKS4.

We found statistically significant linear relationships between MAFAS4-1 and both MAMZS1-1 and MAOKS4-1, with an R^2 of 0.796 and 0.592, respectively (Figure 5.15). Yet, the regression line deviates from the 1:1 ratio. Average moisture contents in MAOKS4-1 are clearly below those in MAFAS4-1. For comparison, the linear relationship between the three access tubes installed in MAFAS4 is displayed in the left graph.

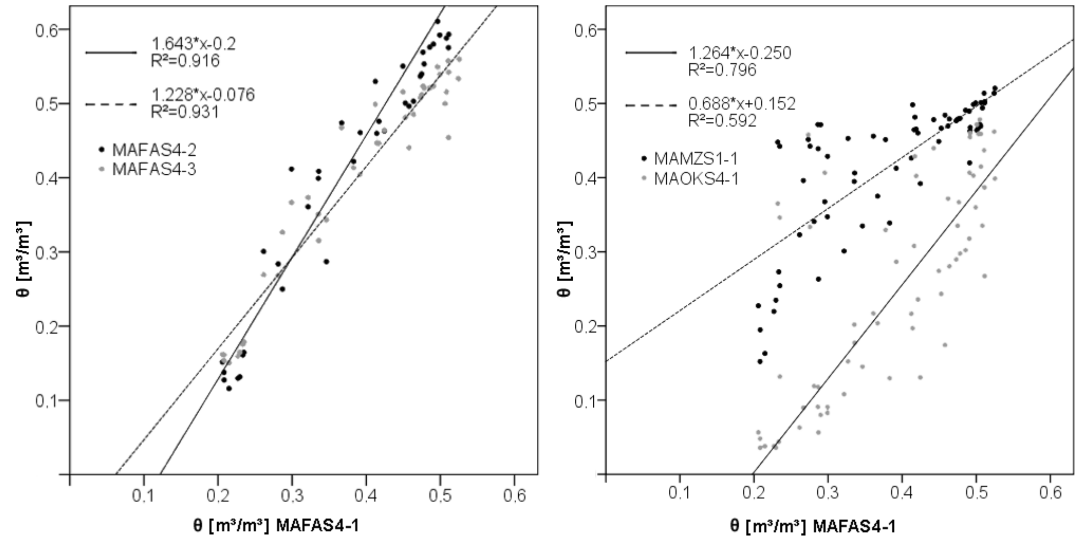


Figure 5.15: Scatter plot of observed soil water content θ at MAFAS4-1 compared to those at four other sites fed by spring water and used for cultivation of irrigated rice and vegetables. Floodplain, Tanzania. MAFAS4-2 and MAFAS4-3 are on the same plot as MAFAS4-1 within a radius of 20 m, while MAMZS1-1 and MAOKS4-1 are located about 200 m away. Locations are displayed in Figure B.6(a). Averages over 10-20-30-40 cm depth and 10 days.

We set up a model in HYDRUS-1D for MAFAS4-1. Throughout the monitoring period, the site itself was under fallow. At the end of November 2009, and then again between April and November 2010, the groundwater level was less than 1 m below the soil surface due to the activation of springs (location of springs in Figure 5.1), which thus controlled soil moisture in the rooting zone (Figure 5.16).

The Nash-Sutcliff model efficiency criteria of 0.72, integrated over 10-40 cm depth, indicates good model performance for the calibration period and satisfying model performance for the validation period (*NSE*=0.53) (Table A.5, Figure 5.16). Thereby, the best model performance for both periods was achieved at a 40 cm depth. The observed moisture contents at 10 cm were unusually high, with values above 0.6 m^3/m^3 (Figure 5.16).

The transfer of the soil water model calibrated for MAFAS4-1 to the neighbouring plots which have similar land use and biophysical settings is not straightforward. This was already expected from the scatter plots in Figure 5.15. For the top 10 cm, an acceptable model prediction was only achieved for MAFAS4-3, which is in the same plot as MAFAS4-1, after the groundwater table dropped in November 2010 (Figure 5.17). During periods with a high groundwater table (April-November 2010), measured and predicted soil moisture contents at 40 cm were in good agreement. However, the large differences between observed and predicted values are obvious for the periods before and after this.

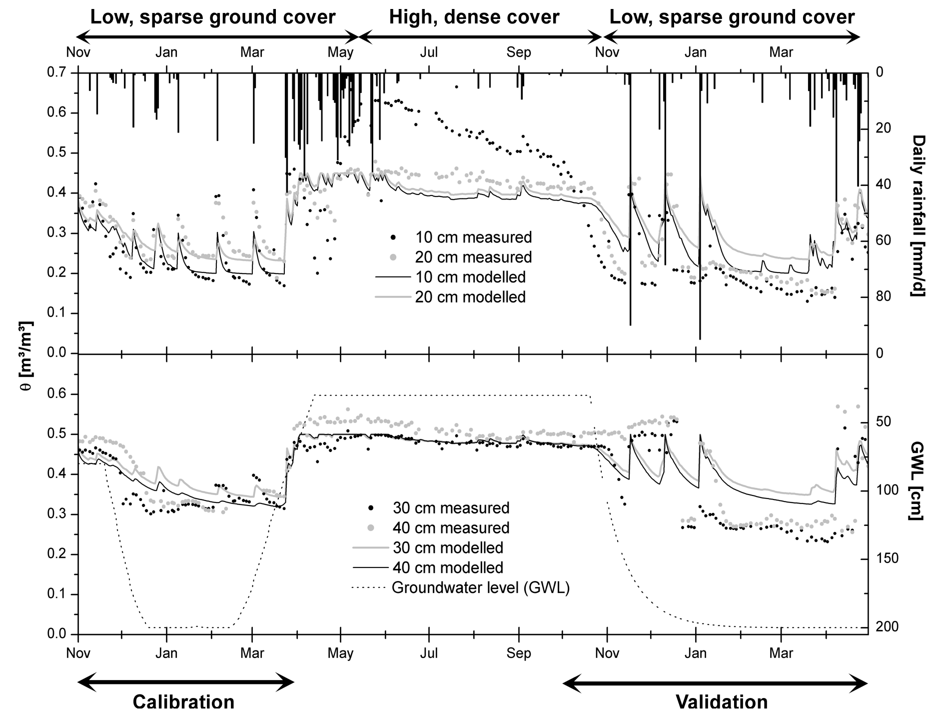


Figure 5.16: Irrigated rice/vegetables (VEG), floodplain, Tanzania: Observed vs. modelled volumetric soil moisture contents θ at 10 to 40 cm depth at site MAFAS4-1. Period 11/2009 to 04/2011. Location is displayed in Figure B.6(a). Measurement depth of piezometer was 200 cm. For GWL>200 cm, estimates were used for modelling.

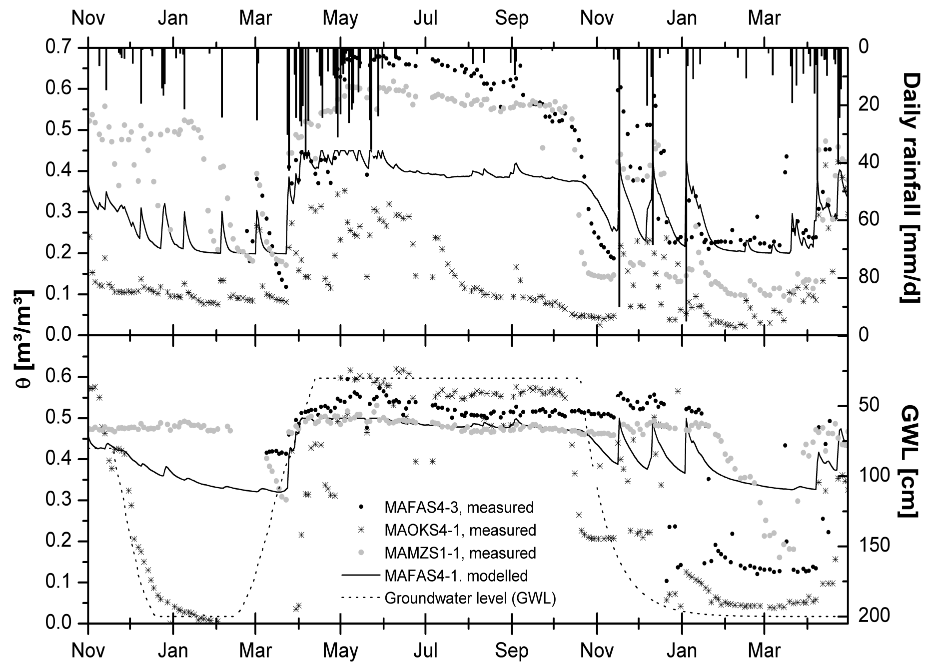


Figure 5.17: Irrigated rice/vegetables (VEG), floodplain, Tanzania: Validation of model calibrated for MAFAS4-1 against measured soil moisture contents θ at 10 (upper graph) and 40 cm (lower graph) depth at neighbouring sites MAFAS4-3, MAOKS4-1, and MAMZS1-1. Period 11/2009 to 04/2011. Locations are displayed in Figure B.6(a).

Upland crops

Three FDR access tubes were installed in the plot MAMZS3 used for cultivation of maize at the western fringe of the floodplain. MAMZS3-1 and MAMZS3-2 are located at about 50 m distance from MAMZS3-3 (Figure B.6(a)). Soil pit 3 is nearby (Table 5.2). The observed groundwater table was deeper than 2 m throughout the observation period.

The correlation between the sites' soil water contents averaged over 10 days was high, with R^2>0.8. The slope of the linear regression equation was close to 1 (left Figure 5.18). MAFAS9-1 is also located at the western fringe of the floodplain and is under maize cultivation as well. Yet, the slope of 1.6 in the regression equation in Figure 5.18 (right picture) indicates higher moisture contents than at MAMZS3-3.

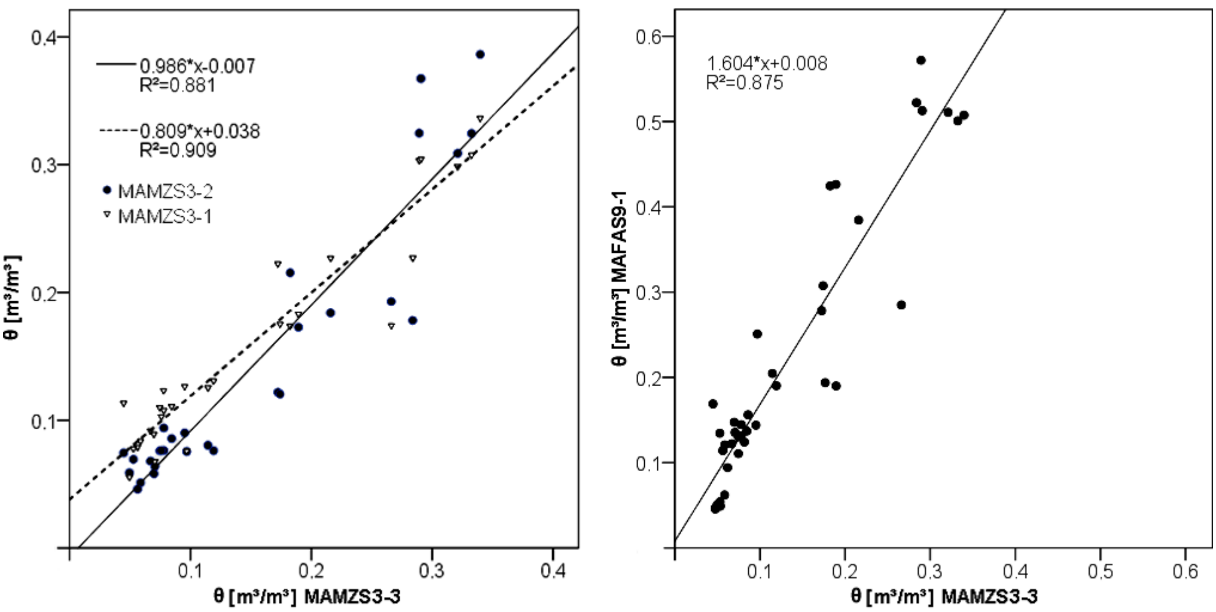


Figure 5.18: Scatter plot of observed soil water content θ at MAMZS3-3 compared to those at three other sites with upland crops (MAMZS3-1, MAMZS3-2, MAFAS9-1). Floodplain, Tanzania. Averages over 10-20-30 cm depth and 10 days. Locations are displayed in Figure B.6(a)

We used Feddes' water uptake model as implemented in HYDRUS-1D with parameters for corn from Wesseling's database. The root growth of the maize was characterized through the assumption that 50% of root growth had been reached after 50% of the growing season (end of March to end of August 2010) had passed. Harvest time was after about 140 days when the maize was dry. Data for the leaf area index (LAI) at six dates was taken from Mourice et al. (2012), as well as data for rooting depth. The temporal variation in modelled soil moisture in the upper 10 cm agrees well with the observations, except for the decline after the long rains (April to June) in 2010 (Figure 5.19). After excluding root water uptake, differences between the observed and predicted responses decreased.

For the long rains in 2010, the predicted maximum soil moisture contents below 10 cm depth were much lower than the observations (Figure 5.19). Therefore, we increased K_s for the upper two soil material layers and θ_s for the second soil material layer (improved parameters in Table A.4). After doing so, we obtained better model performance during this period. However, the model's response during the short rains from November 2010 to January 2011 is yet again not satisfying. The observed moisture content increases by 10 percent after the rainfall event on 16th of November 2011. During the following four weeks, moisture contents drop remarkably, even below the "before-rainfall" level, and do not show any more responses to other rainfall events. The special behaviour at a 40 cm depth of not responding to the rainfall events in December and January was also shown at MAMZS3-1 and MAMZS3-2, but not at MAFAS9-1 (Figure 5.20).

We conclude that the various approaches to parametrize the model below 10 cm depth are only successful for individual periods as can be seen from the overall *NSE* around zero (Table A.5). Notably, model statistics indicate a partial better agreement between modelled time series and measured values at neighbouring sites with the same use than at the model calibration site MAMZS3-3 itself.

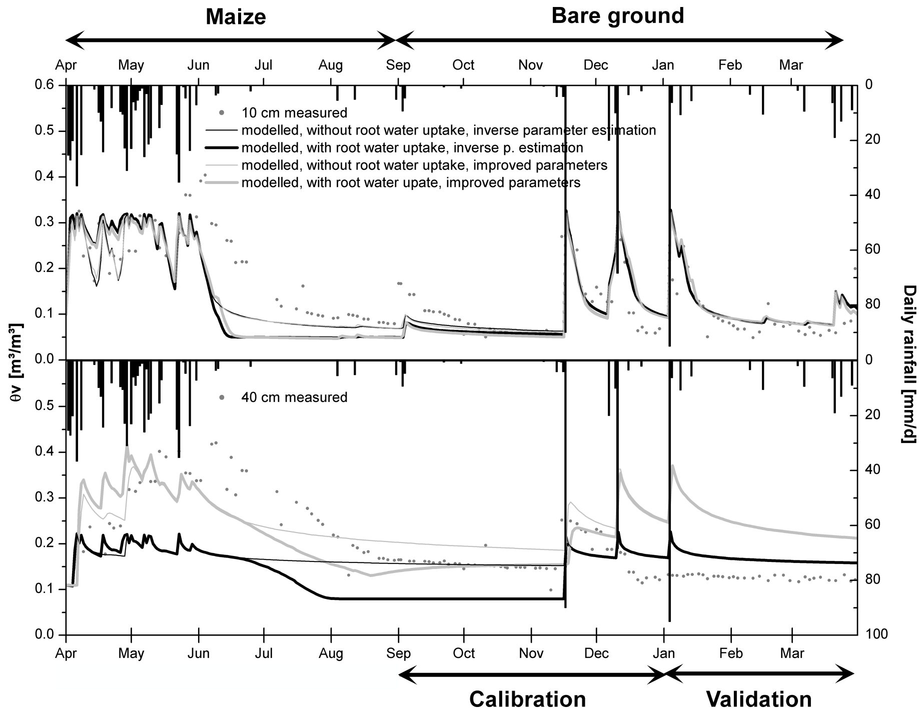


Figure 5.19: Upland crops (MZ), floodplain, Tanzania: Observed vs. modelled volumetric soil moisture contents θ at 10 and 40 cm depth at site MAMZS3-3. Period 04/2010 to 03/2011. Location is displayed in Figure B.6(a). Different parameter sets, with and without consideration of root water uptake.

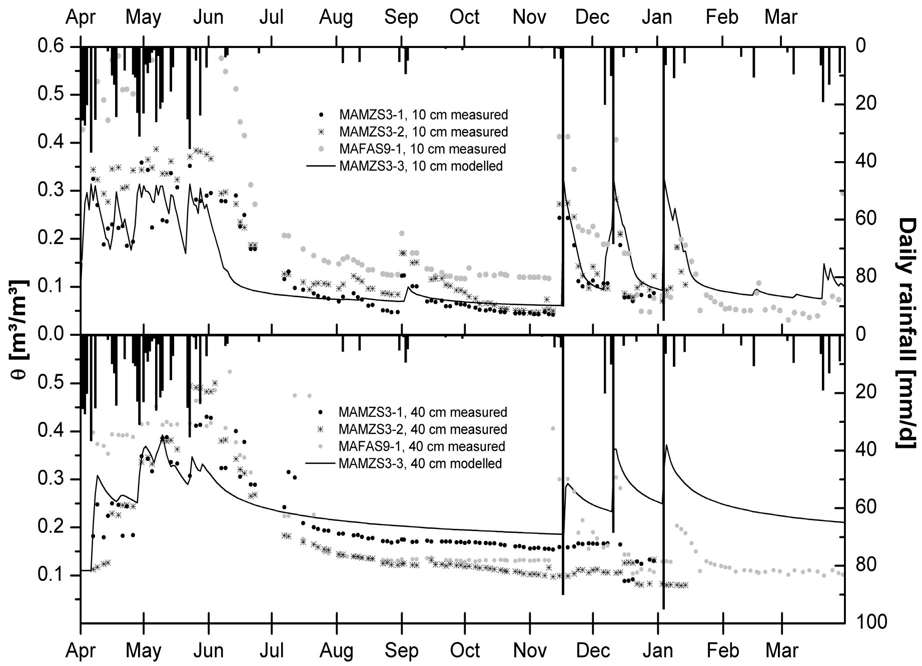


Figure 5.20: Upland crops (MZ), floodplain, Tanzania: Validation of model calibrated for MAMZS3-3 compared to measured soil moisture contents θ at a 10 and 40 cm depth at neighbouring sites MAMZS3-1, MAMZS3-2 and MAFAS9-1. Period 04/2010 to 03/2011. Locations are displayed in Figure B.6(a).

Soil water balances

Based on the soil water models calibrated and validated for the sub-units of the floodplain, we established the water balances for one year, both including and excluding root water uptake (Figure B.7, Table 5.4).
The major difference in the model output of the two approaches is the higher evaporative loss when vegetation cover is lacking. This is even more pronounced for the rainfed rice where the ponding of water occurs. We accounted for this fact in the set-up of the model through the definition of an upper boundary condition which permits to build up a surface-layer of ponding water.

The highest root water uptake among the three sites was determined for the spring-fed site (VEG) which has year-round vegetation cover and a groundwater table close to the surface for prolonged periods (Figures B.7(a) and B.7(c); location of area with springs in Figure 5.1). At the fringe of the floodplain, which is cultivated with maize, the annual sum of root water uptake is the lowest when compared to the other two sites due to the fact that rainwater is the only water supply and vegetation cover existed only until the end of August (Figure B.7(d)). During the long rains from April to June 2010 and during the short rains from November 2010 to January 2011, it can clearly be seen that the soil water storage of the whole profile is filled up through infiltration processes. A substantial increase of cumulated evaporation occurred during the short rains as soil is bare at this time. No bottom flux was observed throughout.

At sites with rainfed rice during the wet season and vegetables during the dry season (RCS), as well as at sites with irrigated lowland rice with occasional vegetable cultivation (VEG), negative bottom flux is associated with drainage from the profile and groundwater recharge (Figure B.7(b) and Figure B.7(c)). On the other hand, a positive bottom flux is associated with capillary rise from the groundwater table. In the rainfed rice, groundwater recharge occurs during the long rains. In the irrigated rice/vegetables plot, the root water uptake through a permanent vegetation cover triggers a positive bottom flux as long as the groundwater table is high. With receding groundwater table starting in November 2010 (Figure B.7(a)), bottom flux becomes zero, while the profile starts draining under conditions of bare ground (negative bottom flux in lower graph).

To conclude, the source of water is a key determinant of the amount of water stored in the soil profile over time. It is lowest at the fringe site and highest at the spring-fed irrigated rice/vegetables site. Over the course of one year, the largest change in soil water storage is observed for the rainfed rice site, where a loss of about 360 mm was calculated, starting from an initial condition of flooding and saturation of the profile (Table 5.4, Figure B.7(b)).

For the irrigated lowland rice with occasional vegetable cultivation, the annual loss is only about 90 mm (Table 5.4, Figure B.7(c)) due to prolonged periods with a positive bottom flux from the shallow groundwater. For the maize site, with the lowest initial water storage at the beginning of the observation period, an increase of 250 mm was calculated (Table 5.4, Figure B.7(d)).

Table 5.4: Annual water balances from HYDRUS-1D for the floodplain, Tanzania. RCS=rainfed lowland rice during wet season and vegetables during dry season, VEG=irrigated lowland rice with occasional vegetable cultivation, UP=upland crops. P=precipitation, ET_a=actual evapotranspiration, ET_p=potential evapotranspiration, G_i=capillary rise, G_o=groundwater recharge, RU=surface runoff, ΔS=change in storage. Error expressed in relation to P

Site	$\boldsymbol{P}$	$\mathbf{ET_a}$	$\mathbf{ET_p}$	$\mathbf{G_i}$	$\mathbf{G_o}$	$\boldsymbol{RU}$	$\boldsymbol{\Delta S}$	**Error**
				mm				%
RCS	932	1159	1901	279	359	-	-363	6
VEG	932	1435	1901	719	108	210	-87	2
UP	932	679	1901	-	-	-	248	<1

The length of growing period (LGP) according to the FAO definition (FAO, 1978) is the period (in days) during a year when precipitation exceeds half the potential evapotranspiration plus the number of days required to evaporate an assumed 100 mm of water stored in the soil after the rains have ceased. The concept is applicable for non-irrigated upland crops.

From mid-March until the end of May 2010, precipitation exceeded evapotranspiration, yielding a LGP of 75 days. At the groundwater-fed plot with irrigated rice and occasional vegetable cultivation, the depletion of the soil water storage after the end of the rains lasted until the beginning of the short rains at the end of November, yielding a length of growing period of 243 days. The growing period in the fringe area was extended by about 40 days to a total of 115 days through the supply from the soil water storage. By then, about 80 mm had been lost from the soil profile through evapotranspiration and further depletion was impeded as indicated by the constant amount of soil water storage.

For the rainfed rice site, the duration of soil saturation was determined to be 115 days.

5.5 Discussion and Conclusions

In this study, we distinguished five sub-units within the floodplain based on the prevailing land use/land cover, landscape position and moisture regime. These were 1) natural vegetation, 2) dry season grazing, 3) rainfed lowland rice during wet season and vegetables during dry season, 4) irrigated lowland rice with occasional vegetable cultivation and 5) upland crops.

Conditions in floodplain wetlands are not static, but experience seasonal, periodical and sporadical alterations and transformations, both naturally and induced by wetland users. For the same site, Mwita et al. (2013) documented a decrease in natural vegetation, a shrinking of permanent swamps and a siltation of open water bodies as a result of human activities for the period between 1976 and 2003. Kuria et al. (2014) reported a cyclic use of the wetland and its periphery, whereby the focus of farming activities alternates between the dry and wet seasons.

Against this background, it was not surprising to see monitoring sites selected as representatives for natural vegetation being converted into plots for the cultivation of staple crops such as taro and for vegetables or paddy rice. Furthermore, the burning of natural vegetation to create grazing grounds for ruminants was commonly encountered, thus affecting the soil moisture regime through the clearing of vegetation. Fringe areas are seasonally used for maize cultivation. After harvesting the rainfed lowland rice in the central floodplain, farmers begin planting vegetables, such as sweet pepper, tomato and okra. These dynamics have to be considered when describing the biophysical characteristics and hydrological dynamics for the five land use sub-units.

The focus of the present study was on time series of volumetric soil moisture content. The advantages and limitations of the application of FDR soil moisture sensors in wetland soils have been discussed in Böhme et al. (2013). Specifically for the floodplain wetland, monitoring the soil moisture status involved the risk of cracks passing by the FDR tubes as a consequence of the swell-and-shrink behaviour of the widely distributed floodplain Vertisols with proportions of the clay size fraction above 40 percent. For this reason, some monitoring sites had to be abandoned. Air gaps between the soil matrix and sensor may lead to an underestimation of volumetric soil moisture contents as the dielectric constant of air is very low as compared to that of water (Blanc and Dick, 2003). However, no trend for the underestimation of volumetric soil moisture contents was observed in the dry range during the sensor calibration procedure.

The field calibration of the capacitance sensor using the gravimetric method yielded an *RMSE* of 0.09 m^3/m^3 for a 10 cm depth and 0.1 m^3/m^3 for a 20-40 cm depth, respectively. While an improvement of sensor accuracy by 0.02 m^3/m^3 in comparison to manufacturer calibration was achieved in the Fluvisol of a Kenyan inland valley wetland (Böhme et al., 2013), no gains in accuracy were achieved in the floodplain soil. As a consequence of the repeated destruction of the measuring devices in the field, dry season grazing areas were not part of the sensor calibration as they were abandoned prior to the first calibration campaign in February 2010. Therefore, the particular characteristics of Vertisols encountered at grazing sites could not be accounted for in the course of the sensor calibration, potentially yielding unreliable, large amplitudes of measured soil moisture contents (Figure 5.10).

Possible reasons for the sensor's measurement error, expressed as an *RMSE* of about 0.1 m^3/m^3, are manifold. As each sampling campaign disturbs soil structure, the sample size per site was generally limited to a maximum of two from the same depth. Only a few samples were collected from frequently flooded natural vegetation. Thus, sites with above average organic carbon content are underrepresented in the sample pool. In other cases, the firmness of clay soils prevented us from taking sufficient core samples in the dry range of soil moisture status. Due to the lack of alternatives, we proceeded with the calibration equation derived from our gravimetric sampling, while being aware that these errors will pervade further analysis of the time series of soil moisture data.

For each of the five sub-units, one FDR-based time series of volumetric soil moisture content in the upper 40 cm of soil depth was presented and HYDRUS-1D soil water models were set up, calibrated and validated, except for natural vegetation. The critical steps for building the model were a) determining the soil hydraulic parameters, b) defining the boundary conditions, for example the variable pressure head at the bottom of the model, and c) specifying the root water uptake model. Particularly the determination of the model's soil hydraulic parameters based on measured soil water retention curves was prone to errors: The firmness of the soil impeded the collection of undisturbed soil cores. The process of sampling and transport might have interfered with soil structure. Also, samples were taken at a time when clayey soil had shrunken. In the process of soil saturation in the laboratory, it has swelled, thus increasing the pressure in the core ring and affecting the soil structure. Furthermore, no soil moisture measurements below a 40 cm depth were available for model calibration and validation with HYDRUS-1D. Therefore, the hydraulic parameters in these depths can only be regarded as estimates, afflicted with unquantified uncertainties.

A major uncertainty in soil water modelling is related to the parametrization of root water uptake through vegetation which determines the difference between potential and actual evapotranspiration and, ultimately, soil water storage. We based the selection of the model parameters on recorded dates of planting and harvesting, the clearance of weeds, the cutting of grass, burning and flooding, as well as estimates of plant height, rooting depth and LAI.

Feddes' parameters for common crops, such as maize (*Zea mays*) and rice (*Oryza sativa*), are available in the HYDRUS-1D database and in literature sources, though they might not fully apply for site conditions. Parameters for "unspecific" ground cover such as weeds are more difficult to specify. A solution for this problem was the use of beans as a "dummy" alternative for weeds.

As expected, model accuracy was higher for the calibration period than for the validation period (Table A.5). Model performance was best for the irrigated rice/vegetables site VEG ($NSE_{calibration}$=0.72, $NSE_{validation}$=0.53) followed by the rainfed rice RCS ($NSE_{calibration}$=0.43, $NSE_{validation}$=0.17). Both are sites with seasonally high groundwater tables. For the irrigated rice/vegetables (VEG) fed by spring water, model accuracy, expressed as *NSE*, was higher at a 40 cm depth than at a 10 to 30 cm depth. For the rainfed rice, flooded by the Mkomazi River and the ponding of rainwater, moisture contents at 10 and 20 cm were best predicted in the model during the calibration period. In the grazing area, the calibrated model may be used for soil moisture prediction in the upper 20 cm with a *NSE* above 0.25. Otherwise, model performance is rather poor. This is likely due to the lack of a dependable FDR sensor calibration for grazing sites.

For the site located in the fringe area of the floodplain and used for the cultivation of maize, only the model results for the upper 10 cm are satisfactory. For the other depths *NSE* was less than zero and *RMSE* larger than 0.1 m^3/m^3. We observed that soil moisture content below 10 cm only increased after the first of three major rainfall events during the period from November 2010 to January 2011. After the following events, the moisture level remained constant. The difficulty in adequately describing the response of the deeper soil material layer may have evolved from the swell-and-shrink-behaviour of the clay soil: After a dry spell, rainwater may penetrate through cracks along the FDR tube and contribute to a significant and immediate increase of moisture levels. While the deep cracks drain or loose water by evaporation, the soil surface has turned into an impermeable layer which prevents further rainfall from penetrating into deeper soil layers. The soil moisture level, except for at the soil surface, drops again to a level equal to or even less than that prior to the first rainfall event.

Only during long periods of rainfall, the moisture front may move downward, saturating the underlaying soil matrix and yielding a rise in soil water content.

Transient dual-porosity or dual permeability models can present a way out of the dilemma of describing periods characterized by the expansion of cracks. However, the difficulty lies in the reproduction of the crack dynamics in shrinking/swelling soils, the determination of crack geometry (crack porosity and the aggregate size) and the parametrization of the preferential flow processes involving a low conductivity matrix and high conductivity voids (Jarvis and Leeds-Harrison, 1990; Novák et al., 2000).

Chen et al. (2014) successfully used a soil moisture model calibrated with measurements from one site for the extrapolation of soil moisture conditions at another site, given that soils, vegetation and rainfall were similar. In our case, the results draw a slightly different picture. The regression analysis of averaged soil moisture contents from positions within the same plot, about 20 to 50 m apart and therefore with similar soil texture, resulted in an R^2 of about 0.9. This indicates similar temporal patterns of soil moisture, yet different average values as slopes of the linear regression equation deviated from 1 (min 0.758, max 1.643) and offsets were different from 0 (min -0.2, max 0.038). Differences in soil moisture patterns, expressed through a smaller R^2 and a deviation from the 1:1 regression line, were observed among sites located more than 200 m apart from each other. Examples are sites with upland crops and with irrigated lowland rice/vegetables which differed in soil textures.

Thus, it can be concluded for our study that predicted and measured time series of soil moisture from adjacent sites showed only a good agreement for those cases where a) the observed soil moisture contents were reliable, i.e. based on accurate sensor calibration, b) the linear regression between time series indicated similar moisture patterns due to similar texture and vegetation cover and c) model calibration was successful. These criteria were met for the rainfed rice, but not for the maize or the irrigated rice/vegetables sites.

From a hydrological perspective, the length of growing period (LGP) as defined by FAO (FAO, 1978) determines the suitability of a site for crop production. When using a reference crop in an area with an equal distribution of rainfall, it is the availability of water from the soil water storage for evapotranspiration which makes the difference among sites within a wetland and among fringe/upland sites and wetland sites.

The water supply from shallow groundwater in the spring-fed areas of the wetland is the cause of the extensive LGP of 243 days, making this area suitable for the cultivation of vegetables as long as aerobic conditions are encountered. In the presence of irrigation infrastructure, the cultivation of irrigated rice is the preferred choice of farmers for using these areas. In the areas located in the central floodplain with rainfed lowland rice during wet season and vegetables during dry season, the flooding of the river and ponding of rainwater, as well as seasonally high groundwater levels replenish soil water storage. Duration of soil saturation was determined to be 115 days, which is sufficient for the cultivation of rainfed lowland rice. For the fringe areas in which rain is the only water source for the cultivation of staple crops, an accumulated increase of 250 mm soil water storage was calculated for the observation period. The duration of moist soil conditions over 115 days allows for cultivating most upland crops. While soil water storage after flood recession provides conditions for the cultivation of short-cycled upland crops following lowland rice in the floodplain center, soil water storage in the fringe areas is insufficient for a second crop after maize.

The findings from this study provide an insight into the potential of floodplain wetlands for crop production. The results may guide sustainable land use management planning in areas allocated for agricultural production, but also in wetland conservation areas allocated for the provision of other ecosystem services. Through the application of a physically-based soil water model such as HYDRUS-1D, even the effect of climate scenarios can be accounted for.

Chapter 6

General discussion, conclusions and recommendations

This thesis aimed at determining the available amount of (soil) water in two agriculturally used wetlands in East Africa and its variability in space and time.

The study sites were selected based on the outcomes of an initial survey. They represent wetland types that are widely distributed in the region and that are regarded as potential agro-developmental resources. While the inland valley type is commonly used for small-scale and subsistence farming (Wood, 2006), the lowland floodplain type is more frequently subject to conversion into larger-scale agricultural production.

6.1 General discussion

6.1.1 Biophysical characteristics of the two wetland types

Both study sites are riverine wetlands. The valley bottom wetland is located in the upper reaches of the Tana River in the humid tropical highland zone of Central Kenya and covers about 10 ha. The floodplain of the Mkomazi River in the sub-humid tropical lowlands of the Pangani Basin in Tanga Region of Tanzania is about 100 times that size.

The first objective of this thesis was to describe the biophysical characteristics of the two wetland sites regarding their meteorological conditions, water sources (surface water, sub-surface water), geomorphic setting and soil attributes.

The study areas receive about 1000 mm of annual rainfall occurring in a bimodal pattern. The water storage in the unsaturated zone of both wetlands is replenished by surface water comprising of overland flow and stream discharge from the Tegu Stream or the Mkomazi River, respectively; of interflow from adjacent slopes, on-site precipitation and - at least locally - a shallow groundwater table. A characteristic feature of the floodplain is the ponding of rainwater for prolonged periods of time caused by impermeable soil and the flat topography.

In the bowl-like shaped head of the inland valley, no distinct stream channel exists. While the upper, narrow section is characterized by a concave valley bottom, the lower wide and flat section appears more like a floodplain with a high density of drainage/irrigation channels.

For the floodplain, the occurrence of diverse soil types such as Vertisol and Gleysol was described, whereby a wide range of soil texture classes was encountered which reflected the varying patterns of sediment deposition. Soil parameters were less heterogeneous among the physical positions in the inland valley bottom, which is dominated by a deep and poorly drained Dystric Fluvisol.

6.1.2 Land use and land cover of the two wetland types

The second research objective was to characterize the dominant types of land use/land cover for the two wetland sites. For the inland valley, the proportions of five land use types regarding moisture requirements/flooding tolerance (duration of saturated conditions) and the growing periods of common crops were mapped. Crop farming was the dominant type of land use in the valley bottom and the adjacent fringe areas, with major proportions used for the cultivation of upland crops, fodder grass and taro (*Colocasia exculenta*) - either in pure stands or in combination.

A network of small canals allows for plot drainage during the rainy season and for supplementary irrigation during the dry season. The area with natural wetland vegetation constituted only a minor share. These portions with wetland vegetation are considered important habitats and reserves for biodiversity. From a hydrological perspective, they serve as freshwater reserves, preserve soil moisture and mitigate the "effects of over-drainage and drought" (Dixon and Wood, 2003, p. 124).

The diversity of land use types in the floodplain has already been demonstrated by the remote sensing study of Mwita (2013). A large part is used for crop production, though the floodplain also contains portions of natural wetland vegetation. A classification of the area regarding dominant water sources and the prevailing land use yielded five groups. These are (1) natural vegetation, (2) dry season grazing land, (3) rainfed lowland rice during wet season and dry season vegetables, (4) dry season vegetables in rotation with irrigated wet season rice and (5) upland crops. Farmers construct infrastructures (bunds, irrigation channels) for the cultivation of rainfed and irrigated rice. Land conversion and the seasonality of use patterns, such as the burning of sites, the clearance of natural vegetation, the activation of former fallows and crop rotation, were observed during the monitoring period.

Thus, it can be concluded that a multiple-use pattern is practiced in both wetlands. Such a wetland use strategy, which comprises different portions allocated for crops, grazing, and natural vegetation, is favourable to a single-use strategy, such as seasonal agriculture or the complete conversion into commercial cropping via drainage (Dixon and Wood, 2003).

6.1.3 Application of a Frequency Domain Reflectometry sensor to monitor soil moisture

To capture the diversity of wetland habitats from a hydrological perspective, particularly with respect to plant growth, it is essential to pay attention to the plant available water storage in the rooting zone. By controlling penetrability, temperature regime and aeration status, the last of which is closely linked to the rate of mineralization processes and nutrient release, soil moisture status is not only relevant to the water supply for plants, but is also closely linked to the physico-chemical conditions of plant growth (Robinson et al., 2008; Thomsen et al., 1999).

As soil water availability determines a wetland's suitability for agricultural production and discriminates wetland agriculture from upland farming, I monitored volumetric soil moisture content in the rooting zone of crops. The portable FDR sensor was used for point measurements in access tubes. A procedure for sensor calibration had to be developed and tested for its applicability in wetland soils. This arose from the lack of available data on calibrating FDR sensors for specific wetland conditions, such as low bulk densities, high clay contents and high to very high organic C contents. Calibration accuracy, expressed as Root Mean Squared Error (RMSE) was better for Tegu (RMSE=0.07 m^3/m^3) than for Malinda (RMSE=0.09-0.10 m^3/m^3).

6.1.4 Seasonal soil moisture status in the context of biophysical site characteristics and land use and land cover

The relationship between seasonal soil moisture status, hydro-meteorological conditions, soil attributes, landscape position and types of land use/land cover was to be established under the fourth research objective.

Despite its small size, the Tegu inland valley is characterized by a diversity of micro-hydrogeomorphological conditions related to soil moisture. Thus, a range of conditions is encountered for different agricultural land use along and across the wetland.

Sites with a high groundwater level and negligible seasonal variation yield periods of soil saturation of more than 9 months. These areas should be left for natural vegetation or fallow, unless drainage measures are applied. Saturated/flooded conditions for up to 9 months are suitable for taro cultivation, such as encountered in the mid section of the valley. For purely upland crop cultivation, aerated conditions are required and soil saturation should not exceed 6 months, such as in the well-drained fringe areas. The highest annual variation of topsoil moisture content was encountered along the lower slopes, where the permanent wilting point was reached towards the end of the dry season. Particularly the lower, floodplain-like section of the valley as well as the mid section, are characterized by a dense drainage network and the cultivation of upland crops partially in rotation with taro. The impact of water abstraction for irrigation on the discharge of the Tegu Stream was demonstrated during this research.

The HYDRUS-1D soil water model was applied in the floodplain wetland to establish the hydrological relationship between meteorological conditions, water fluxes and seasonal soil water storage, while at the same time addressing gaps in the time series of measured soil moisture. The central floodplain, used for rainfed rice during wet season and vegetable cultivation during dry season, was flooded by the Mkomazi River and by ponding of rainwater during the long rainy season and high moisture contents prevailed into the dry season. In the spring-fed area, used for irrigated rice and the occasional cultivation of vegetables, capillary rise from a shallow groundwater table contributed substantially to the annual soil water storage of the site. Sites with year-round high moisture levels and prolonged periods of flooding are characterized by natural wetland vegetation. For the site with dry season grazing, poor model performance did not allow for determining an annual soil water balance.

6.1.5 Suitability of the study wetlands for crop production

The fifth objective was to draw conclusions on the suitability of the two wetland sites for crop production. Generally, farmers in the Tegu and Malinda wetlands are knowledgeable about the hydrological functioning of their wetland farms and suitable crops. They actively manage the network of channels for drainage and irrigation, build bunds for lowland rice cultivation and construct raised plots to avoid excess moisture for upland crops.

Based on the observed times series of soil moisture and groundwater level, the optimal use types for specific locations were predicted for the Tegu inland valley. Discrepancies between the observed soil moisture conditions and optimal use were related to the cultivation of upland crops at sites more suitable for the cultivation of flood resistant taro or taro cultivation at sites with very short periods of aerobic conditions. This bears the risk of crop failure due to flooding.

The length of the growing period (LGP)/period of soil saturation in the floodplain was derived from the outcomes of the soil water model. LGP varied between 243 days for sites with a prevailing shallow groundwater table and 115 days for fringe areas where rainwater provides the only source for replenishing the soil water storage. The soil water availability in the fringe area allows for the cultivation of most upland crops. However, in these areas soil water storage is insufficient for dry season cultivation after the harvest of maize. Soil saturation in the central floodplain lasted for 115 days, thus allowing for the cultivation of rainfed lowland rice. Soil water storage after flood recession may permit the cultivation of short-cycled upland crops following lowland rice.

In summary, taro and rice, and to a lesser extent sorghum and sweet potato, are recommendable crops for wetland agriculture as they can tolerate a degree of water-logging and contribute to the food self-sufficiency of the wetland communities (Dixon and Wood, 2003; Wood, 2006). For lowland floodplains, the amount of available soil water supports the cultivation of lowland rice during the rainy season, possibly in rotation with vegetables or upland cereals during the dry season, or alternatively leaving the land as grazing fallow to nomadic pastoralists.

6.2 Conclusions

This thesis demonstrated the necessity, potential and limitations of multi-method approaches to deriving information on soil water availability in two wetland types in East Africa. Considering the results from the previous chapters, the following conclusions can be drawn:

- Seasonal and temporal (soil)-water availability in wetlands depends on the wetland type and is controlled by the prevailing meteorological conditions, landscape position within the wetland, water sources and soil attributes.

- Land use is closely related to soil water availability. Farmers risk crop failure due to excess moisture in cases where adequate water management infrastructures are not in place or crops are not adapted to prevailing moisture conditions.

- Capacitance sensors for monitoring volumetric soil moisture content require site-specific calibration prior to their application on wetland soils. The calibration procedure yielded a higher accuracy for the inland valley than for the floodplain.

- The application of electromagnetic soil moisture sensors, the determination of soil hydraulic properties and the modelling of soil water dynamics is impeded by the shrink-swell-behaviour of the clay substrates of wetland soils.

- A soil water model was used to relate meteorological conditions of the floodplain wetland to soil attributes, land cover and seasonal soil water storage. Its overall performance was moderate. The best results were obtained for the area with a shallow groundwater table and the cultivation of irrigated rice/vegetables. The modelling of a site with dry season grazing yielded poor results.

- The suitability of a wetland site for crop production is determined by the crop to be cultivated, the length of flooded or saturated soil conditions, the period of sufficient residual soil moisture after flooding and the existence of infrastructures for water management.

It was not possible to provide an answer as to the question of which is the most appropriate way to use the region's wetlands wisely. A use of wetland resources will always come along with alterations of the wetland from its natural state. The concepts of Integrated Watershed Management provide the framework for the implementation of a sustainable agricultural land and water management for economic development that ensures that the impacts on the wetland's ecological functionality remain at a minimum. Quantifying the amount of water stored in the soil and the proportion that can be used for agricultural production without negatively impacting the ecosystem contributes to a sustainable wetland management.

6.3 Recommendations

- To understand a wetland's hydro(geo)logical functioning, the wetland must be closely studied in the context of its catchment, thereby necessitating the application of multi-method approaches.
- Long-term time series of hydrometeorological variables and observations of land use patterns are necessary for evaluating the impacts of agricultural land and water management practices on the hydrological regimes of wetlands and their catchments. Thus, the limited viability of conclusions drawn from datasets of months to a few years must be considered.
- Information on stream discharge in floodplain wetlands should be collected and related to flood extent and flood duration. This allows for the prediction of hydroperiods[1], which are in turn related to soil water availability, at the various locations within the floodplain.
- Datasets of gravimetric soil moisture samples covering a wide range of moisture conditions are required to improve the accuracy of future FDR sensor calibration procedures. Outcomes of the procedure of field calibration should be compared to those of laboratory calibration.
- In addition to portable FDR sensors suitable for monitoring a large number of sites, the permanent installation of FDR sensors at specific soil depths and connected to data loggers is recommendable, as they provide much more detailed information on the temporal variation of soil water storage over the soil profile.
- Remotely sensed soil moisture data, in addition to *in-situ* measurements, are an important component of studies on field-scale soil water dynamics.
- More attention should be given to research on the effects of shrink-swell-behaviour on the hydraulic properties of wetland soils with high clay contents.
- Two-dimensional soil water models permit the incorporation of lateral water fluxes and can establish the relationship between seasonal soil dynamics and landscape position. Thus, the application of two-dimensional, as opposed to one-dimensional, soil water models may allow for a more detailed evaluation of soil water availability for agricultural production. However, the benefits of such an approach come at the cost of higher data requirements. Both aspects must be weighed against each other.

[1]"Hydrological dynamics, often expressed as the hydroperiod (referring to the frequency and duration of flooding) and the pattern (especially depth and variation) of waterlogging (sometimes also included in the term hydroperiod) [...]"(Barker and Maltby, 2009, p. 115)

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Appendix A

Tables

Table A.1: Number of sites with FDR access tubes included in three calibration campaigns (camp.) of profile probe in the floodplain, Tanzania. NAT=natural vegetation, GZ=dry season grazing, RCS=rainfed lowland rice during wet season and dry season vegetables, VEG=irrigated lowland rice and dry season vegetables, UP=upland crops. NONE=sites which could not be assigned to one of the previous categories. No calibration for grazing due to disturbance of sites.

Depth cm	**Sub-unit** (Number of sites)	02/2010 camp. 1	10/2010 camp. 2	05/2011 camp. 3	02/2010+ 10/2010	02/2010+ 05/2011	10/2010+ 05/2011	02/2010+ 10/2010+ 05/2011
10	NAT(6)	1	2	3	-	-	1	1
	GZ(9)	-	-	-	-	-	-	-
	RCS(12)	4	4	5	1	-	1	2
	VEG(13)	5	7	10	-	1	2	4
	UP(13)	4	6	6	1	-	1	3
	NONE(7)	2	1	4	-	1	-	1
20	NAT(6)	1	-	-	-	-	-	-
	GZ(9)	-	-	-	-	-	-	-
	RCS(12)	4	3	-	2	-	-	-
	VEG(13)	5	7	-	4	-	-	-
	UP(13)	4	5	-	3	-	-	-
	NONE(7)	2	-	-	-	-	-	-
30	NAT(6)	1	-	3	-	1	-	-
	GZ(9)	-	-	-	-	-	-	-
	RCS(12)	4	3	4	1	1	1	1
	VEG(13)	4	5	10	-	2	2	2
	UP(13)	4	5	6	1	1	1	2
	NONE(7)	2	-	4	-	2	-	-
40	NAT(6)	-	-	-	-	-	-	-
	GZ(9)	-	-	-	-	-	-	-
	RCS(12)	-	1	-	-	-	-	-
	VEG(13)	-	3	-	-	-	-	-
	UP(13)	-	1	-	-	-	-	-
	NONE(7)	-	-	-	-	-	-	-

Table A.2: Model parameters and goodness-of-fit statistics for linear relationships[a] between square root of the soil bulk electrical permittivity $\sqrt{\epsilon}$ and volumetric water content θ obtained gravimetrically. Floodplain, Tanzania. Bold numbers designate statistically significant linear relationship at 5% level. NAT=natural vegetation, RCS=rainfed lowland rice during wet season and dry season vegetables, VEG=irrigated lowland rice and dry season vegetables, UP=upland crops.

Sub-unit type	**Depth**	a_1	a_0	R^2	F	p**-value**
	10 cm	3.894	2.628	0.240	$F(1,4)=1.263$	0.324
NAT	20-40 cm	-	-	-	-	-
	10-40 cm	3.894	2.628	0.240	$F(1,4)=1.263$	0.324
	10 cm	5.177	2.904	0.407	$F(1,11)=7.551$	**0.019**
RCS	20-40 cm	9.140	1.894	0.284	$F(1,8)=3.180$	0.112
	10-40 cm	4.918	3.178	0.296	$F(1,21)=8.818$	**0.007**
	10 cm	7.698	1.312	0.765	$F(1,20)=64.945$	**<0.0005**
VEG	20-40 cm	7.742	2.338	0.418	$F(1,26)=18.671$	**<0.0005**
	10-40 cm	7.235	2.003	0.364	$F(1,49)=28.031$	**<0.0005**
	10 cm	6.756	1.755	0.840	$F(1,14)=73.265$	**<0.0005**
UP	20-40 cm	4.459	2.728	0.345	$F(1,22)=11.572$	**0.003**
	10-40 cm	5.707	2.269	0.559	$F(1,38)=48.227$	**<0.0005**
	10 cm	6.381	1.843	0.626	$F(1,61)=102.243$	**<0.0005**
all	20-40 cm	8.354	2.090	0.663	$F(1,61)=119.951$	**<0.0005**
	10-40 cm	6.026	2.326	0.434	$F(1,128)=98.225$	**<0.0005**
all except	10 cm	7.186	1.609	0.626	$F(1,53)=165.110$	**<0.0005**
NAT	20-40 cm	8.354	2.090	0.663	$F(1,61)=119.951$	**<0.0005**

[a] $\sqrt{\epsilon} = a_0 + a_1 \times \theta$

Table A.3: Infiltration rates f from measurements with double-ring infiltrometer in the Malinda floodplain, Tanzania. Information on dominant water source given. Proportion of sand-size and clay-size fraction and bulk density (ρ_S) at measurement sites provided for topsoil Top (0-20 cm) and subsoil Sub (20-40 cm), NAT=natural vegetation, GZ=dry season grazing, RCS=rainfed lowland rice during wet season and dry season vegetables, VEG=irrigated lowland rice and dry season vegetables, UP=upland crops.

Code	**Water source**	**Site**	f	**Clay**		**Sand**		ρ_S	
				Top	Down	Top	Down	Top	Down
			cm/h	%	%	%	%	g/cm^3	g/cm^3
NAT	flooding from Sangai area	17	18.8	51	63	28	20	0.79	1.49
		18	0.6	47	73	24	8	0.61	1.25
		19	4.0	51	65	24	18	0.70	1.53
GZ	ponding of rainwater	1	0.5	54	68	27	23	1.14	1.32
		2	2.5	54	62	23	29	1.14	1.36
		13	3.0	23	35	68	58	1.67	1.57
		14	1.6	25	39	66	52	1.63	1.55
		27	0.8	49	55	26	24	1.09	1.23
	flooded by Mkomazi River and its tributaries	5	2.0	50	54	35	35	1.20	1.37
		6	5.0	60	56	23	27	1.14	1.28
		11	2.0	49	51	24	26	1.08	1.24
		12	2.6	53	63	20	14	1.10	1.33
RCS	flooded by Mkomazi River and its tributaries	3	5.8	30	10	45	89	1.10	1.47
		4	12.9	6.0	36	91	56	1.19	1.52
		9	4.1	54	52	31	33	1.03	1.38
		10	2.6	56	56	29	35	1.17	1.50
		26	26.5	41	9	44	90	0.87	1.62

Table A.3: (continued)

Code	**Water source**	**Site**	f	**Clay**		**Sand**		ρ_S	
				Top	Down	Top	Down	Top	Down
			cm/h	%	%	%	%	g/cm^3	g/cm^3
VEG	Mkundi springs	20	9.0	33	43	52	48	1.06	1.55
		21	6.5	37	41	52	50	1.07	1.50
		22	2.1	39	41	48	46	1.04	1.20
		23	1.2	37	39	52	50	1.16	1.13
		24	18.3	37	43	50	46	1.25	1.36
UP	no flooding	7	10.5	36	38	41	49	1.17	1.45
		8	5.3	36	36	45	53	1.12	1.41
		15	6.9	23	27	64	62	1.24	1.62
		16	16.1	23	27	64	64	1.35	1.60
		25	16.9	25	29	62	58	1.23	1.57

Table A.4: Parameter sets and boundary conditions (Bc.) in HYDRUS-1D. Floodplain, Tanzania. Parameters explained in Chapter 5.3.5. NAT=natural vegetation, GZ=dry season grazing, RCS=rainfed lowland rice during wet season and dry season vegetables, VEG=irrigated lowland rice and dry season vegetables, UP=upland crops. Explanation boundary conditions: Upper (U.) Bc.: 1=Atmospheric Bc. with surface layer, 2=Atmospheric Bc. with surface runoff; Lower (L.) Bc.: 1=Free drainage, 2=Variable pressure head. *parameters estimated with ROSETTA neural network prediction and cross-checked with parameters estimated from measured retention curves. Note that the model soil material layers may differ from pits' soil layers in Table 5.2

Model material layer	**Depth**	θ_r	θ_s	α	n	K_S	l	**U.Bc.**	**L.Bc.**
	cm	cm^3/cm^3		cm^{-1}		cm/d			
GZ: MAGZS1									
1	0-13	0.07	0.39	0.001	1.10	0.1	0.1	1	1
2	13-65	0.09	0.56	0.001	1.42	5.1	0.7		
3	65-130*	0.10	0.61	0.024	1.29	6.5	0.5		
4	130-200*	0.10	0.43	0.026	1.11	0.2	0.5		
RCS: MARCS1-1									
1	0-12	<0.01	0.44	0.012	1.32	43.0	0.3	1	2
2	12-25	0.05	0.50	0.012	1.32	43.0	0.3		
3	25-35	0.01	0.55	0.050	1.20	36.9	0.2		
4	35-90	0.01	0.55	0.014	1.26	10.26	0.2		
5	90-140*	0.01	0.30	0.020	1.19	15.6	0.5		
6	140-170*	0.01	0.44	0.020	1.10	43.0	0.5		
7	170-200*	0.01	0.44	0.028	1.94	100.0	0.5		
VEG: MAFAS4-1									
1	0-15	0.06	0.45	0.020	1.20	106.0	0.5	2	2
2	15-25	0.10	0.45	0.020	1.20	79.0	0.5		
3	25-35	0.01	0.50	0.010	1.10	21.0	0.5		
4	35-120	0.10	0.50	0.010	1.20	5.0	0.5		
5	120-200*	0.01	0.45	0.030	1.20	1.0	0.5		

Table A.4: (continued)

Model material layer	Depth	θ_r	θ_s	α	n	K_S	l	U.Bc.	L.Bc.
	cm	cm^3/cm^3		cm^{-1}		cm/d			
UP: MAMZS3-3									
1	0-20 (initial)	<0.01	0.33	0.017	1.39	22.0	0.2	2	1
1	0-20 (improved)	<0.01	0.33	0.017	1.39	50.0	0.2		
2	20-65 (initial)	0.06	0.23	0.066	1.35	7.0	6.5		
2	20-65 (improved)	0.06	0.45	0.066	1.35	10.0	0.5		
3	65-130*	0.08	0.37	0.029	1.15	5.4	0.5		
4	130-150*	0.08	0.33	0.030	1.13	1.9	0.5		
5	150-200*	0.08	0.34	0.034	1.13	3.2	0.5		

Table A.5: Statistics for calibration and validation period in HYDRUS-1D models from the floodplain, Tanzania. NAT=natural vegetation, GZ=dry season grazing, RCS=rainfed lowland rice during wet season and dry season vegetables, VEG=irrigated lowland rice and dry season vegetables, UP=upland crops. R^2=Coefficient of determination. *RMSE*=Root mean squared error, *NSE*=Nash-Sutcliffe model efficiency coefficient.

	Calibration			**Validation**		
Sub-unit/Depth	R^2	***RMSE***	***NSE***	R^2	***RMSE***	***NSE***
cm		m^3/m^3			m^3/m^3	
GZS: MAGZS1	15/03/2009-18/07/2009				-	
inverse						
10	0.37	0.04	0.31	-	-	-
20	0.39	0.10	0.27			
30	0.22	0.18	<0	-	-	-
40	0.03	0.42	<0	-	-	-
all depths	0.01	0.24	<0	-	-	-
ROSETTA						
10	0.26	0.10	≪0	-	-	-
20	0.18	0.13	<0	-	-	-
30	0.24	0.21	<0	-	-	-
40	0.21	0.45	<0	-	-	-
all depths	0.04	0.26	<0	-	-	-
HYPROP						
10	0.29	0.09	≪0	-	-	-
20	0.37	0.11	0.07	-	-	-
30	0.28	0.22	<0	-	-	-
40	0.01	0.49	≪0	-	-	-
all depths	0	0.28	<0	-	-	-
RCS: MARCS1-1	11/06/2010-02/05/2011			15/03/2009-22/02/2010		
10	0.57	0.08	0.54	0.18	0.12	<0
20	0.54	0.06	0.50	0.44	0.09	0.40
30	0.33	0.10	0.28	0.42	0.20	0.23
40	0.08	0.14	0.06	0.14	0.28	0.12
all depths	0.44	0.10	0.43	0.23	0.19	0.17

Table A.5: (continued)

Sub-unit/Depth cm	Calibration R^2	*RMSE* m^3/m^3	*NSE*	Validation R^2	*RMSE* m^3/m^3	*NSE*
RCS: MARCS1-2				01/03/2010-31/03/2010		
10	-	-	-	0.75	0.08	0.68
20	-	-	-	0.73	0.14	0.45
30	-	-	-	0.76	0.08	0.67
40	-	-	-	0.49	0.11	0.21
all depths	-	-	-	0.71	0.10	0.69
RCS: MARCS1-3				01/03/2010-31/03/2010		
10	-	-	-	0.78	0.11	0.54
20	-	-	-	0.61	0.22	0.20
30	-	-	-	0.87	0.08	0.76
40	-	-	-	0.68	0.08	0.63
all depths	-	-	-	0.71	0.12	0.58
VEG: MAFAS4-1	01/11/2009-31/03/2010			01/10/2010-30/04/2011		
10	0.63	0.05	0.59	0.50	0.08	0.13
20	0.59	0.04	0.49	0.62	0.08	0.36
30	0.62	0.04	0.41	0.55	0.09	0.21
40	0.82	0.04	0.67	0.61	0.08	0.49
all depths	0.72	0.04	0.72	0.65	0.08	0.53
VEG: MAFAS4-3				23/02/2010-17/04/2011		
10	-	-	-	0.60	0.15	0.21
20	-	-	-	0.65	0.08	0.60
30	-	-	-	0.57	0.11	0.38
40	-	-	-	0.60	0.11	0.47
all depths	-	-	-	0.44	0.12	0.42
VEG: MAMZS1-1				01/11/2009-30/04/2011		
10	-	-	-	0.52	0.15	0.31
20	-	-	-	0.52	0.07	0.49
30	-	-	-	0.54	0.06	0.52
40	-	-	-	0.34	0.07	<0
all depths	-	-	-	0.46	0.09	0.41

Table A.5: (continued)

	Calibration			Validation		
Sub-unit/Depth	R^2	*RMSE*	*NSE*	R^2	*RMSE*	*NSE*
cm		m^3/m^3			m^3/m^3	
VEG: MAOKS4-1				01/11/2009-30/04/2011		
10	-	-	-	0.28	0.20	≪0
20	-	-	-	0.36	0.21	≪0
30	-	-	-	0.59	0.25	<0
40	-	-	-	0.69	0.20	0.1
all depths	-	-	-	0.44	0.22	<0
UP: MAMZS3-3	01/09/2010-31/12/2010			01/01/2011-31/03/2011		
10	0.7	0.03	0.68	0.66	0.03	0.64
20	0.39	0.14	≪0	0.09	0.19	≪0
30	0.22	0.16	≪0	0.30	0.21	≪0
40	0.02	0.07	≪0	0.19	0.11	≪0
all depths	0.06	0.11	≪0	0	0.15	≪0
UP: MAMZS3-1				01/04/2010-30/12/2010		
10	-	-	-	0.62	0.06	0.55
20	-	-	-	0.44	0.09	<0
30	-	-	-	0.14	0.12	≪0
40	-	-	-	0.36	0.07	0.24
all depths	-	-	-	0.36	0.09	<0
UP: MAMZS3-2				01/04/2010-14/01/2011		
10	-	-	-	0.65	0.07	0.53
20	-	-	-	0.54	0.11	<0
30	-	-	-	0.39	0.15	≪0
40	-	-	-	0.30	0.11	0.10
all depths	-	-	-	0.29	0.11	<0
UP: MAFAS9-1				01/04/2010-31/03/2011		
10	-	-	-	0.56	0.18	0.14
20	-	-	-	0.49	0.12	0.33
30	-	-	-	0.35	0.12	0.32
40	-	-	-	0.30	0.11	0.29
all depths	-	-	-	0.30	0.14	0.26

Appendix B

Figures

(a) (b) (c) (d)

Figure B.1: Installation of piezometer: (a) Drilling of 2 m deep hole; (b) Perforation of pipe. Slots are covered with a bandage to prevent clogging; (c) Bottom of hole up to upper end of slotted portion of pipe filled up with gravel; (d) Operational piezometer.

(a) (b)

Figure B.2: Measurement devices for soil moisture and saturated hydraulic conductivity: (a) Profile Probe PR2 with handheld device HH2; (b) Compact Constant Head Permeameter.

(a) (b)

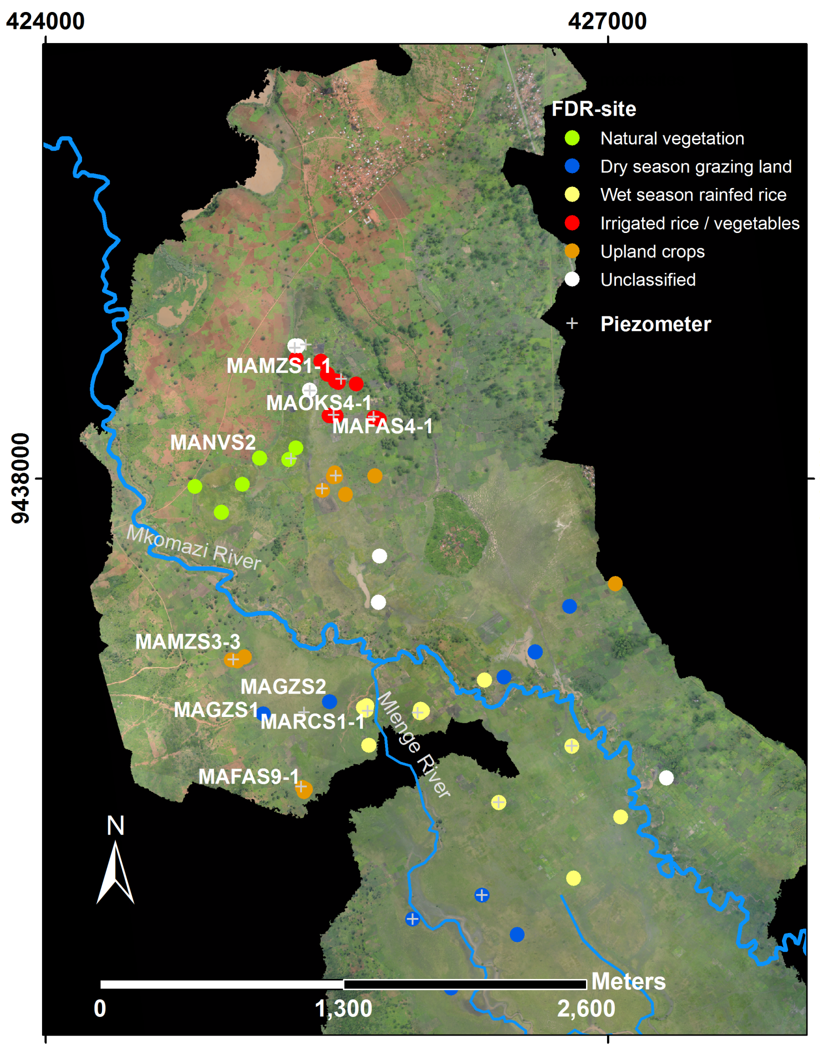
Figure B.3: Double-ring method for *in-situ* measurement of infiltration rate: (a) Application of double-ring method; (b) Cracks at grazing site in floodplain, Tanzania.

(a) (b)

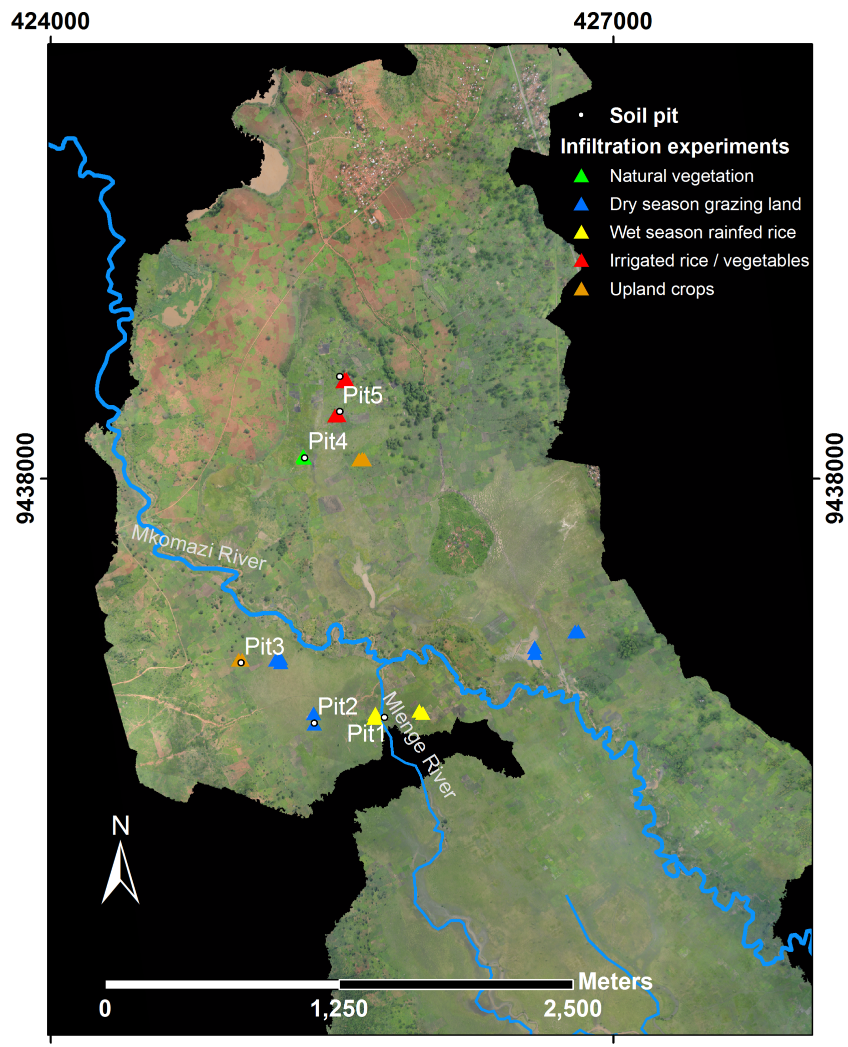
Figure B.4: V-notch weir for discharge measurement of Tegu Stream, Kenya: (a) Normal condition, upper weir; (b) Overflow of lower weir during rainy season.

(a) (b)

Figure B.5: Setting of the weather stations: (a) Schoolyard of Kanyama Secondary School at Tegu inland valley wetland, Kenya; (b) Schoolyard of Kwasunga Primary School at Malinda floodplain wetland, Tanzania.



(a)



(b)

Figure B.6: Location of hydrological monitoring and sampling sites in the Malinda floodplain, Tanzania. Aerial photos from SWEA-project: (a) Location and land use/land cover (LULC) categories of sites for FDR-based soil moisture monitoring. Labelled sites are referred to in Chapter 5.4.3; and (b) Location of soil pits and sites for infiltration experiments with double-ring infiltrometer.

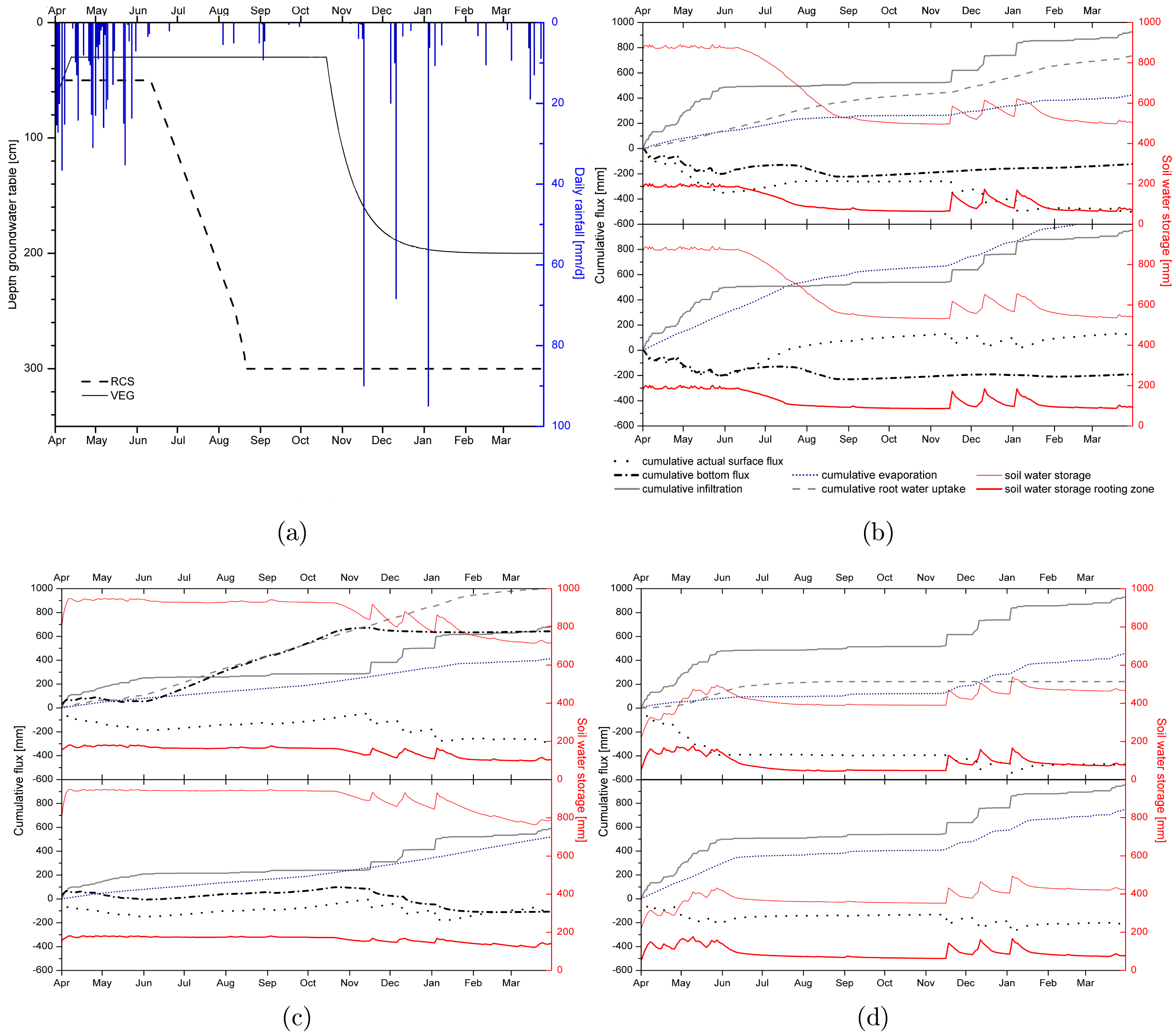


Figure B.7: Water fluxes and soil water storage for sub-units of the floodplain, Tanzania. Root water uptake has been incorporated in the upper graph, while the lower graph shows conditions for bare soil. Surface runoff was close to zero and is not displayed. Period 04/2010 to 03/2011. (a) groundwater level plotted against daily rainfall for rainfed rice (RCS) and irrigated lowland rice with occasional vegetable cultivation (VEG). Measurement depth of piezometer was 200 cm. For GWL>200 cm, estimates were used for modelling; (b) rainfed lowland rice during wet season and vegetables during dry season (RCS); (c) irrigated lowland rice with occasional vegetable cultivation (VEG); (d) upland crops; no bottom flux was encountered.

Figure B.8: Representative sites for land use classes in the Tegu inland valley, Kenya: (a) Overview of valleyhead; (b) Upper section with dominance of napier grass; (c) Mid section with stream channel and extensive cultivation of taro; (d) Fringe area in the mid section; (e) Grazing area in the mid section; (f) Bunding at slopes in the upper and mid section.

(a)

(b)

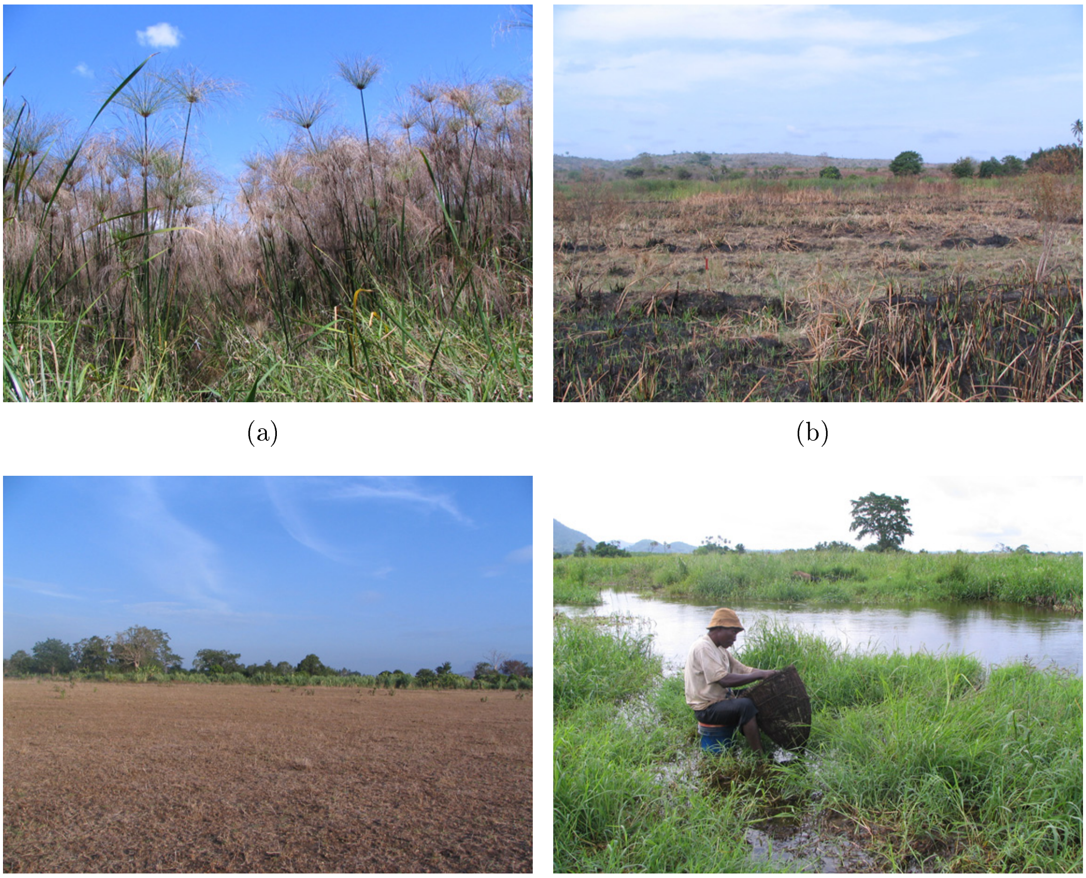
(c)

(d)

(e)

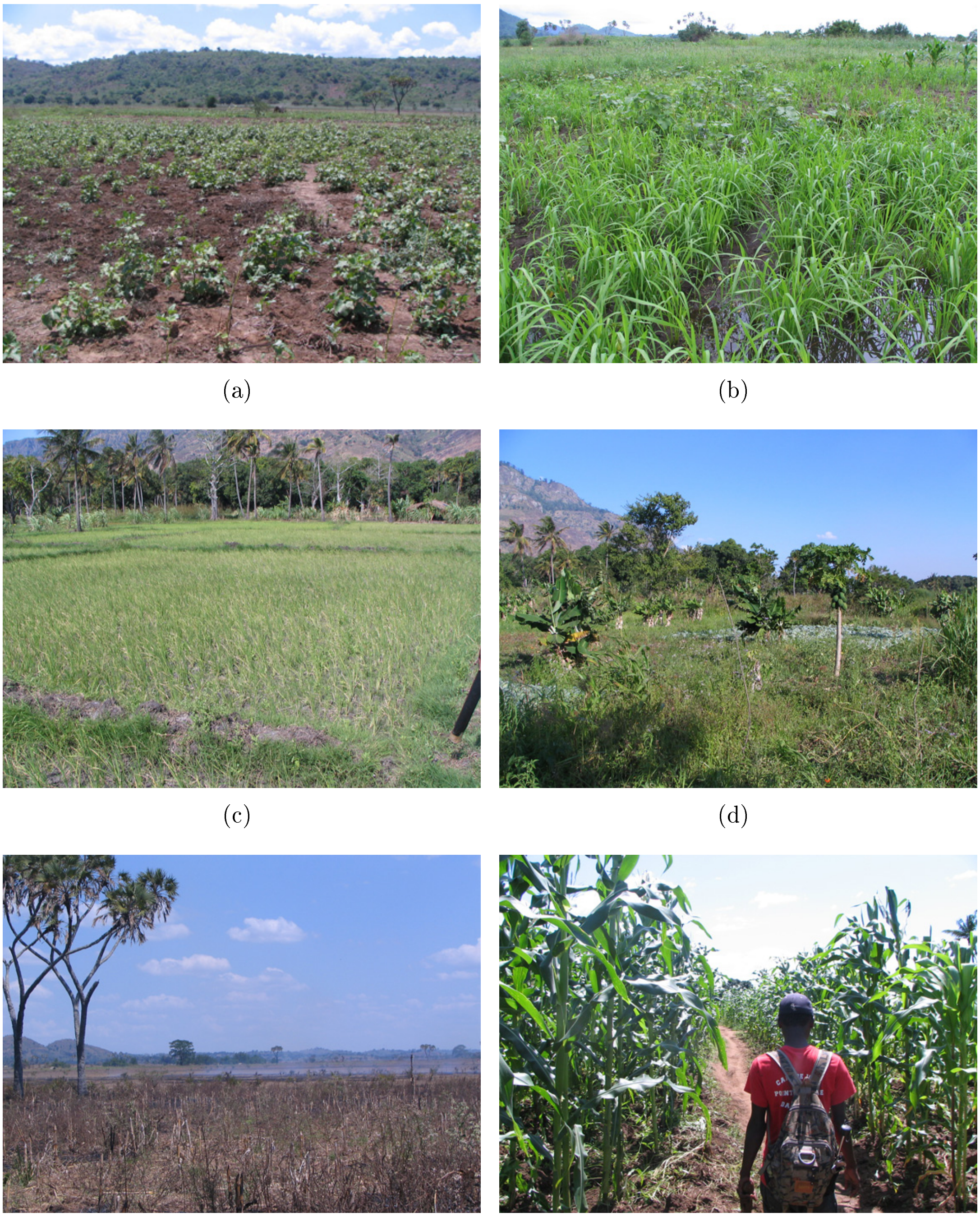
(f)

Figure B.9: Representative sites for land use classes in the Tegu inland valley, Kenya (cont.): (a) Slopes in the mid section cultivated with coffee and napier grass; (b) Slopes in the lower section cultivated with staple crops (maize, beans); (c) Cultivation of upland crops (beans) in the flat lower valley section; (d) Cultivation of diverse crops in the flat lower valley section; (e) Tegu Stream in the lower section during dry season; (f) Extensive flooding of the lower section during rainy season.



(a) (b) (c) (d)

Figure B.10: Representative sites for land use classes in the Malinda floodplain, Tanzania: (a) Papyrus swamp (NAT); (b) Burnt natural vegetation (NAT); (c) Grazing area during dry season (GZ); (d) Fishing in a tributary of Mkomazi River during flooding of the grazing area (GZ).



(a) (b) (c) (d) (e) (f)

Figure B.11: Representative sites for land use classes in the Malinda floodplain, Tanzania (cont.): (a) Central floodplain with cultivation of vegetables during the dry season (RCS); (b) Central floodplain with rainfed rice after the long rainy season (RCS); (c) Area with springs, used for the cultivation of irrigated rice (VEG); (d) Area with springs, used for vegetable cultivation (VEG); (e) Fringe area after harvest of maize (UP); (f) Fringe area with matured maize (UP).