Impacts of Global Climate Change on the Water Resources of the Bunyala plains

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Preface

SANET is executing a pilot action as part of the Advancing Capacity to support Climate Change Adaptation (ACCCA) project funded by UNITAR: Improving decision-making processes through climate change scenario generation in the Bunyala flood plains of western Kenya.

This project seeks to determine ways in which a community's adaptive capacity can be increased by providing decision support that builds upon local knowledge and skills; strengthening farmers' organisations through scenario generation and water management strategies training; and involving stakeholders in examining solutions to existing and future challenges to climate change.

FutureWater contributes to this project by developing an Integrated Water Resource Management Planning Tool (for generating climate change scenarios) for improved planning and management of sustainable food supply and sustainable livelihoods; and training materials for technical support in the maintenance and implementation of the planning tool and the facilitation of stakeholder workshops for exploring scenarios and supporting local water and cropping decisions. These activities are expected to contribute to more effective agricultural decision-making and sustainable water management strategies.

Summary

Climate change will have a pronounced effect on Africa's water resources and has a direct impact on water management strategies, which play a key role in the enhancement of national economic development and increases in farmers' real income. These management strategies are a crucial part of medium-term and long-term agricultural policies.

This study focuses on the climate change impacts and adaptation options in the Nzoia river catchment in western Kenya and on the downstream Bunyala plains specifically. The Bunyala plains are located on the shores of Lake Victoria and contain a rice irrigation scheme. Rice production yields can be increased under certain rain-fed and irrigated conditions; however climate change is expected to increase the magnitude and frequency of droughts. The area is one of the most densely populated regions in Kenya and East Africa. Poverty levels and HIV/AIDS prevalence are very high. Communities living in the area are vulnerable to climate change impacts on water resources (floods, droughts). The projected climate change is analyzed, the impacts on the water balance of the Nzoia river catchment are evaluated and a flood analysis is performed for the Bunyala plains. These analyses provide the boundary conditions for an assessment of the impacts and adaptation options for agriculture. A number of important conclusions can be drawn based on this analysis.

Based on the analysis of historical data on temperature it is concluded that no significant temperature trend has been observed at four different locations across Kenya from 1979 to 2000. This is remarkable as it is to be expected that temperature trends would follow global warming trends. For precipitation a significant negative trend are observed at all stations. Some care is warranted with these conclusions as they are based on reanalysis data that are derived using a combination of model results and observations.

It is very likely that the climate will change in the Nzoia river catchment and increases in precipitation and temperature are consistently predicted by a suite of global circulation models. Remarkably climate change will provide important opportunities for both rain fed and irrigated agriculture in the downstream Bunyala plains as water availability will increase significantly.

The Nzoia river catchment is the wettest catchment of Kenya and the flow duration curve is typical of a catchment that suffers from rain floods. The river discharge is lowest from January to March and relatively constant throughout the other months of the year with a peak in May. Rainfed agriculture is the largest water consumer (52% of total rainfall) in the catchment and urban water use is negligible. In total 27% of total rainfall is discharged into Lake Victoria.

The analysis with the water resources management tool WEAP reveals the hydrological impact of climate change. All scenarios show very significant increases in river discharge (36% in 2050 and 51% in 2090) and thus climate change will increase water availability which can provide important opportunities for both rain fed and irrigated agriculture. It is not likely that the planned expansion of the irrigation systems in the Bunyala plains will suffer from water shortage due too low flow conditions in the Nzoia river basin. However, the analysis also showed that a completely shift to rain fed agriculture is not feasible.

The crop model analysis showed that is possible to undertake a swift yet comprehensive impact and adaptation assessment to climate change for crop production. The number of scenarios that can be analyzed is virtually unlimited and is mainly restricted by quality of data. Obviously,

if real investments are considered a more detailed analysis is required where the focus should be on obtaining additional data, further calibration of the model and intensified contacts with farmers and water managers to improve scenario definition. Based on the analysis it is very clear that given the fact that water is abundant there is sufficient scope for expanding the irrigated area. The analysis revealed also that rainfed rice is even under the expected increase in rainfall not feasible. Finally it was concluded that the impact of the combined effect of CO2 fertilization, and the increase in rainfall, more rice can be produced under climate change conditions as expected in 2050.

A recent study from IFPRI (International Food Policy Research Institute, 2009) revealed that on a global scale agricultural productivity investments of around US$ 7 billion are required to overcome the negative impact of climate change on food production. Based on the results of the combined AquaCrop and WEAP analysis it is clear that the Bunyala irrigation scheme is a favourable place to invest in agricultural production: water is abundantly available now and in the future, and farmers interest and expertise is available. Besides the required investment in irrigation infrastructure a limiting factor might be distance to markets.

Flooding is however the major threat to these developments. Security levels of the embankments protecting the Bunyala plains are already relatively low and floods occur regularly. The already planned extension of the agricultural systems and the projected increase in extreme discharges and population growth increase the vulnerability of the Bunyala plains significantly. An important component of irrigation extension plans should be on a thorough flood risk assessment and an increase of security levels of the embankments to higher standards.

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1 Introduction

Climate change has a direct impact on water management strategies, which play a key role in the enhancement of national economic development and increases in farmers' real income. These management strategies are a crucial part of medium-term and long-term agricultural policies. Rice production yields can be increased under certain rain-fed and irrigated conditions; however climate change is expected to increase the magnitude and frequency of droughts. Rice production in the Bunyala Flood Plains, situated within the Lake Victoria basin, is one of the most densely populated regions in Kenya and East Africa. Poverty levels and HIV/AIDS prevalence are very high. Communities living in the area are vulnerable to climate change impacts on water resources (floods, droughts). Rice production is both a staple and a cash crop which ensures food security to the households by earning income. However, the main water resource for rice production, Nzoia River is affected by climate change (deforestation at source), population increase and pollution (paper and sugar factories). In addition, floods (and associated silt deposition), damages to physical infrastructure (roads, canals, pumping stations) bring about additional challenges (resettlement, malaria, clean water challenges etc) in the area.

In this study the observed climate change from 1961-2000 is analyzed and a number of climate change scenarios are derived. Subsequently these climate change scenarios are used to assess the future changes in water resources of the Nzoia river catchment in general and the Bunyala floodplains specifically using an advanced water resources management tool. A specific chapter is then dedicated to flooding and how flooding may change in the future. The report is concluded by an assessment of climate change and increased CO_2 levels on rice production systems on the Bunyala floodplains and several adaptation scenarios are evaluated.

2 Study area

2.1 Nzoia River catchment

The Nzoia river catchment is located in Western Kenya reaches from the shores of Lake Victoria (1140 meter) to the Western Highlands of Kenya (4300 meter). The Nzoia River has length of around 334 km. The downstream part of the Nzoia catchment is the wettest area of entire Kenya with average rainfall exceeding 1500 mm in some locations. The highlands towards the east of the catchment are much drier (Figure 1). The catchment is located just north of the equator and the average annual temperature is 22°C distributed evenly throughout the year. The total area of the catchment is 12752 km^2.

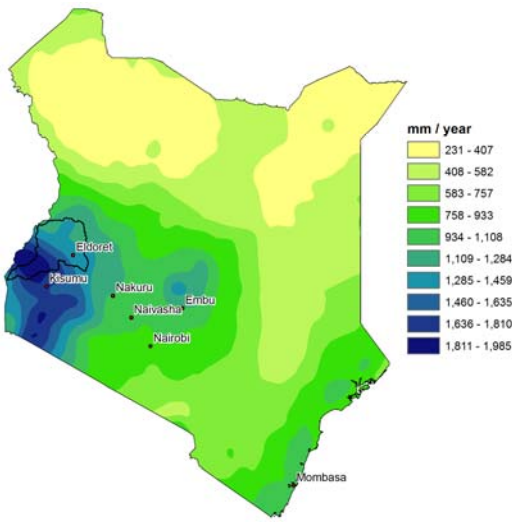


Figure 1 Average annual precipitation in Kenya and location of the Nzoia river catchment

Figure 2 shows the annual precipitation and the monthly distribution spatially average for the entire catchment. There is considerable inter-annual variation of precipitation ranging from 874 mm in 2004 to 1300 mm in 2000. January is the driest month (47 mm) and April the wettest (162 mm). The precipitation data are acquired from the FEWS-RFE2.0 database for Africa[1].

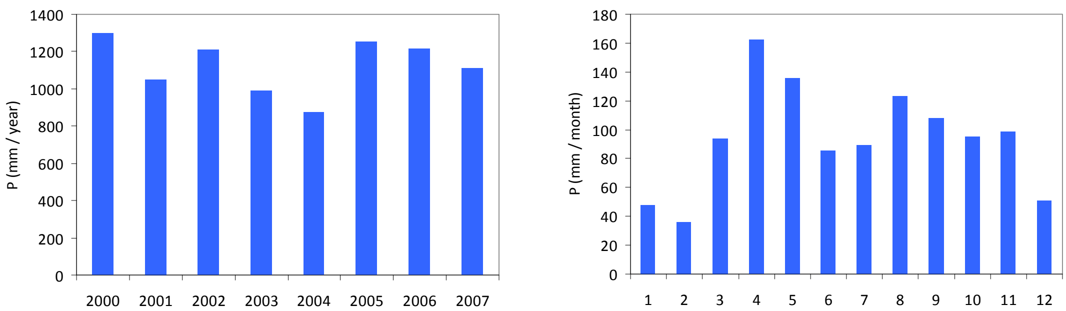


Figure 2 Average annual precipitation for the Nzoia catchment from 2000-2007 and the average monthly distribution.

[1] http://www.cpc.noaa.gov/products/fews/data.shtml

In the study region, there has been an increase of population over the last three decades with an estimated population density of 221 persons / km^2 in 2002 (Odada et al., 2004). The dominant land use in the region is agriculture and the main food crops include maize, sorghum, millet, bananas, groundnuts, beans, potatoes, and cassava while the cash crops consist of coffee, sugar cane, tea, wheat, rice, sunflower, and horticultural crops. Dairy farming is also practiced together with traditional livestock keeping. The catchment provides water for domestic, (rural and urban water supply), agriculture, industrial, and commercial sectors. Thus, changes in the supply of rainfall, whether in total, in intensity or in frequency, could have serious consequences for the agricultural, industrial, and environmental sectors (Githui, 2008).

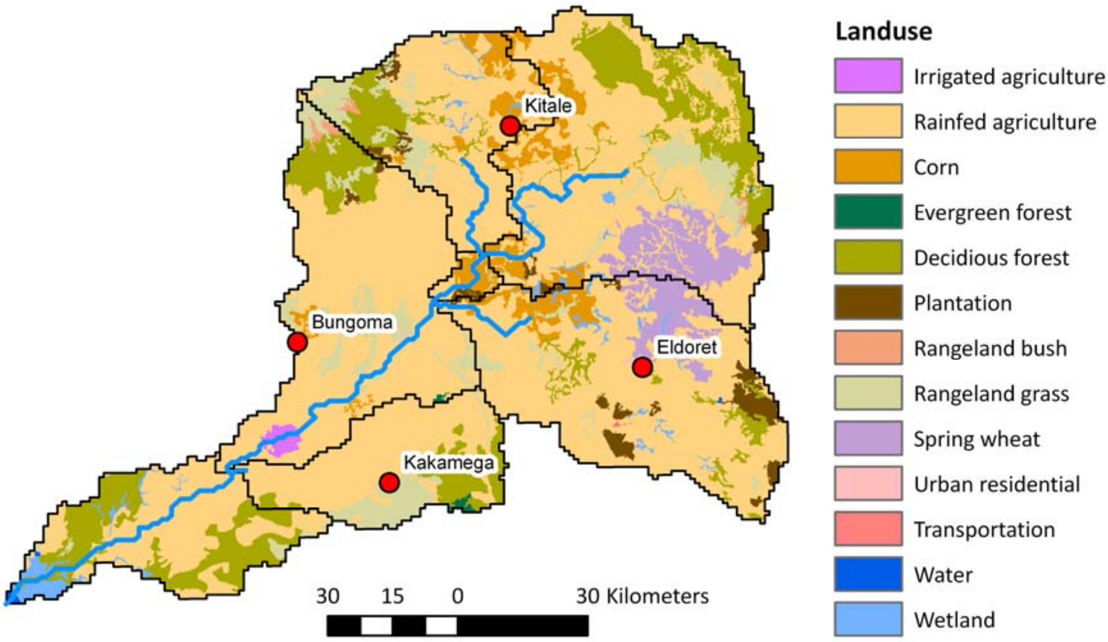


Figure 3 Land use of the Nzoia river catchment

Figure 3 shows the land use map of the Nzoia river catchment. The largest part of the catchment consists of rain fed agriculture (74%), around 14% is forested and the remaining classes are predominantly rangelands, wetlands, and built up areas. The major cities in the catchment are Eldoret, Kakamega, Bungoma and Kitale.

2.2 Bunyala rice irrigation scheme

The Bunyala rice irrigation scheme is located in the most downstream area of the Nzoia river catchment (Figure 4, Figure 5). In red the catchment boundary is shown. The irrigation scheme is located south of Nzoia River and north of the Yala swamp. The irrigation scheme is divided into two parts. One part (212 ha, 250 farmers) is operated by the government and is locally referred to as the nuclei and is located outside the main irrigation scheme. The largest part is operated by the Munaka Community Based organization (CBO). The total area that is managed by the Munaka CBO is 2428 ha, of which currently only 304 ha is in operation. The irrigation scheme is subdivided in blocks and details are given in Table 3. There is a pumping station with a total capacity 0.6 m^3 s^{-1} of which approximately half is currently used.

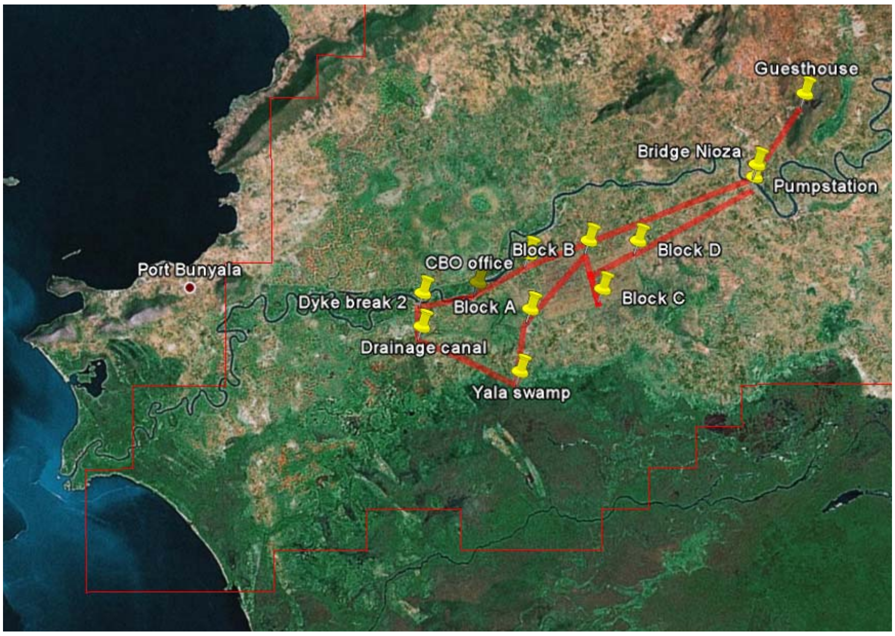


Figure 4 Location of the Bunyala rice irrigation scheme

Table 1 Blocks of the Bunyala irrigation scheme managed by the Munaka CBO

Section	# farmers	Area (ha)
Munaka A	153	55
Munaka B	86	40
Munaka C	115	162
Munaka D	104	40
Munaka E	21	6
Total	**479**	**304**

The 304 hectares that are operational are exclusively used for rice cultivation. Every year two crops are cultivated: one crop cycle from February to July and one from September to December. The farmers use both ammonium suplhate (250 kg / ha) and ureum (125 kg / ha) as fertilizer. Carbofuran is used as pesticide on the rice seedlings. The average yield per crop cycle is 5535 kg ha^{-1} and the market price is 0.41$ kg^{-1}. Most farmers sell their crops to the Kenya cereal board or on the local market if the prices drop too much. The total production cost per hectare is shown in Table 2.

Table 2 Rice production costs (source: personal communication Munaka CBO; 1 ksh = 0.013$)

Cost	Cost ($ /ha)
Operation and maintenance (irrigation)	130.48
Rotoration	114.17
Seed	61.16
Fertilizer	195.72
Chemicals	65.24
Total	**566.78**

Given these figures an average farmer with a farm size of 0.63 ha (304/479) can generate an income of 2163 $ $year^{-1}$ (2 x 0.63 x (5535 x 0.41 – 566.78)) in a normal year. The total average production of the entire system is currently around 7000 ton / year. Given the current fertilizer application and taking into account the fertile vertisol soils significant yield improvements are feasible.

The most important reasons for crop failure are hail stones, rice blast and yellow mot virus. Climate change is locally not yet perceived as a major reason for crop failure. The farmers have however observed a change in the rainy seasons. The total annual rainfall amount has remained constant, but there has been a delay in the onset of the rainy season. In the past there were two clearly demarcated wet seasons (April and November), now this is less clear and this is also confirmed by the FEWS rainfall estimates. Around 60% of the total arable land is used for rain fed agriculture. These farmers adapt to climate change by delaying the sow dates. As temperature is fairly constant throughout the year the consequences are not severe. The farmers also report an increase in peak flows in the Nzoia River. There is a dike along the final 20 km towards Lake Victoria protecting the Budalangi plains from flooding, but the dike is regularly breached. In both May 2007 and November 2008 heavy rainfall in the upstream areas of the Nzoia catchment resulted in severe flooding of the Budalangi plains displacing around 10 thousand people.

Figure 5 The Bunyala rice irrigation scheme: Munaka CBO (top left), irrigation canal (top right), transplanting rice (bottom left), pumping station (bottom right).

There are plans to extend the Bunyala irrigation scheme and increase the current operational area from 304 ha to 2428 ha. In addition there is a National Irrigation Board project funded by the World Bank that aims at increasing the irrigated area downstream of the current system by 3500 ha at both sides of the Nzoia River. Currently a feasibility study for the new scheme in Lower Nzoia has been finalized and preparation for implementation is ongoing. Clearly climate change will play a crucial role in the successful implementation of these proposed extensions.

There is also a considerable area that is used for rainfed farming towards the Yala swamp. The main crops that are cultivated here are maize and sorghum with an average yield of 4400 kg ha^{-1}. Besides flooding issues the rain fed farmers also experience problems due to droughts and delayed onset of the rainy seasons.

3 Climate change

3.1 Methodology

In the framework of the WeAdapt project (www.weadapt.org) the Climate Change explorer was developed. The Climate Change Explorer (CCE) is a tool that aims to facilitate the gathering of climatological information and its application to adaptation strategies and actions. The CCE packages data access routines with guidance and customized analytical and visualization procedures. It is designed to simplify the tasks associated with the extraction, query and analysis of climate information, thereby enabling users to address issues of uncertainty when devising policies and strategies, and also when implementing actions.

The CCE encourages users to focus on the conditions, assumptions and uncertainties of model-based statements about future climate. This enables them to evaluate the relevance of the information, the appropriateness of response options, and to make an informed assessment of risk. It presents an envelope analysis of ensembles which defines a domain of plausible climate change from a wide range of multi-model projections. It is driven by the search for climate spaces relevant to the localities and systems of interest. Exposure and adaptation are context-specific. An interactive exploration of the climate science is therefore critical to the provision of useful information, and appropriate contextualization for decision support.

The CCE was used to download downscaled Global Circulation Model (GCM) data for the A2 scenario for two different future time slices (2046-2060 and 2080-2100). The GCM simulations were performed in the framework of the IPCC 4th assessment report (AR4) (Randall, 2007). Because projections of climate change depend heavily upon future human activity, climate models are run against scenarios (Nakicenovic, 2000). There are 40 different scenarios, each making different assumptions for future greenhouse gas pollution, land-use and other driving forces. Assumptions about future technological development as well as the future economic development are thus made for each scenario. These emission scenarios are organized into families, which contain scenarios that are similar to each other in some respects. IPCC assessment report projections for the future are made in the context of a specific scenario family. Here we use the commonly used A2 scenario. The A2 scenarios are of a more divided world. The A2 family of scenarios is characterized by:

- A world of independently operating, self-reliant nations.
- Continuously increasing population.
- Regionally oriented economic development.
- Slower and more fragmented technological changes and improvements to per capita

Although used in the development of scenarios to understand the impacts of transient dynamics on specific ecosystems, the direct application of GCM output has been relatively limited in impact studies due to their coarse spatial resolution (which in many cases fails to adequately represent critical regional variations), temporal resolution (only one or sometimes two time series are available), computational and technical requirements of using these data, and, until recently, difficulties with data access . Downscaling approaches have emerged as a solution to address the needs of the impacts research community. This techniques combines observational data from a climatological normal period (usually 30 years between 1969 and

1999) to empirically or dynamically represent a specific climate station's response to a collection of GCM scenarios.

The downscaling method applied to the data distributed within the Climate Change Explorer is an empirical approach The approach is based on the assumption that a quantifiable relationship exists between large scale (synoptic) circulation patterns (the first order drivers) and local climatic conditions- which can be used to simulate local responses accurately. Other variability and patterns that influence local conditions (not captured in the synoptic signals) are introduced via a stochastic (semi-random) element into the calculations. A complete technical description of the approach is presented in Hewitson and Crane (2006). The strength of empirical downscaling is that it does not require much computing power as once the data have been downscaled they can be disseminated, it allows easy comparison of many different GCM projections and it provides data at the level of individual stations. This means that the range of uncertainty in the projections can be compared to look for where the models agree on the sign of change, thus more confident decisions can be made.

Table 3 Description of the 6 different GCMs used in the analysis.

Model	**Description**
CCMA CGCM3.1	Canadian Centre for Climate Modeling and Analysis, the third generation coupled global climate model (CGCM3.1 Model, T47).
MPI ECHAM5	Max Planck Institute for Meteorology, Germany, ECHAM5 / MPI OM
CNRM CM3	Meteo-France, Centre National de Recherches Meteorologiques, the third version of the ocean-atmosphere model (CM3 Model)
CSIRO MK3.0	CSIRO Atmospheric Research, Australia, MK3.0 Model
IPSL CM4	IPSL/LMD/LSCE, France, CM4V1 Model
GFDL CM2	NOAA Geophysical Fluid Dynamics Laboratory, CM2.0 coupled climate model

In this study the Kakamega station was selected which is located in the centre of the catchment. For this station data of six different GCMs (Table 3) were downloaded using the CCE and compared with the control period. The monthly change fields for precipitation, temperature and reference evapotranspiration were then superimposed on the time-series used to run the WEAP model.

3.2 Historical trends

First we analyze the historical trends in precipitation and temperature from 1979 to 2007 forfor Nairobi, Mombassa, Nakuru and Kakamega based on CCE data. In Figure 6 the historical precipitation and precipitation trends are shown. Kakamega is the wettest, while Nairobi is the driest. Mombassa is the hottest and Nakuru the coldest. It is interesting to note that at all stations a negative trend in precipitation is observed while most climate models predict an increase in precipitation over the coming decades (3.3). In addition no discernable trends are observed in temperature while an increase of 0.5°C is to be expected over this period. Some care is warranted as these data are based on so called reanalysis data that are a mix of observation and model data. In addition observation are subject to measurement errors.

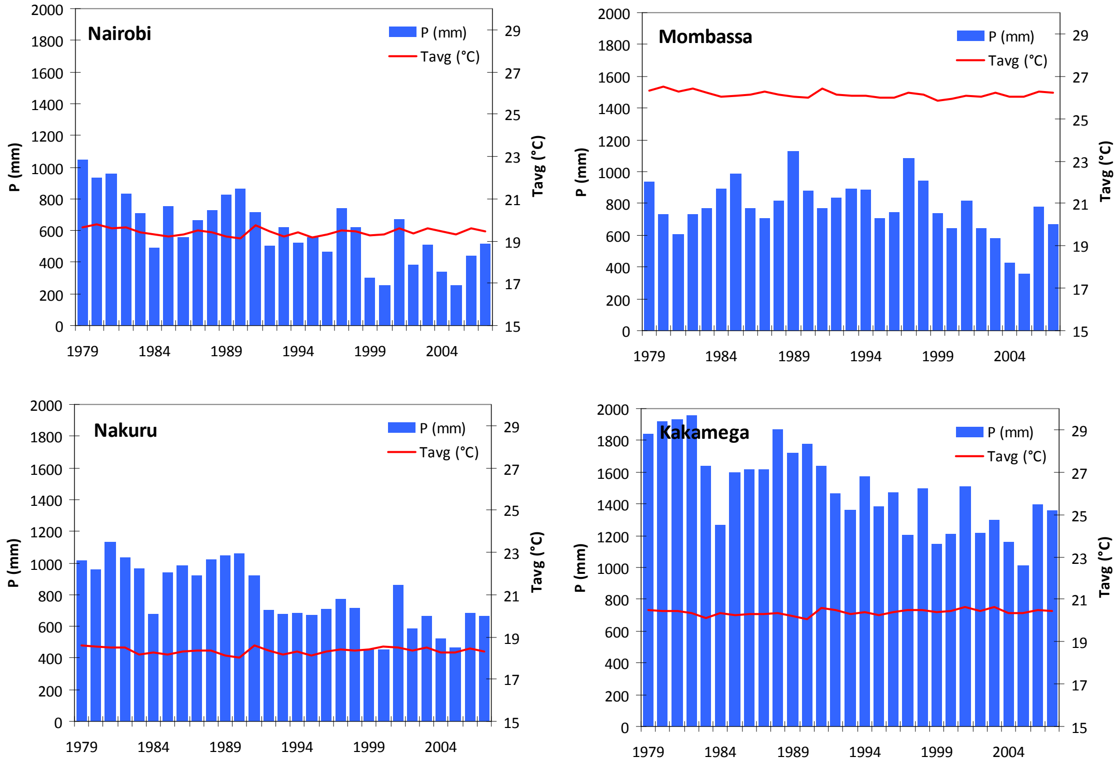


Figure 6 Historical precipitation and temperature trends from 1979 to 2007 for Nairobi, Mombassa, Nakuru and Kakamega based on data derived from the climate change explorer

3.3 Future scenarios

3.3.1 Overview kenya

All of Africa is likely to warm during this century and the warming is likely to be larger that than the global annual mean warming throughout the continent and throughout the seasons. Annual precipitation is likely to decrease in most of Africa, however in East Africa and Kenya an increase in mean annual rainfall is projected (IPCC, 2007). Kenya is tropical and the central phenomenon is the seasonal migration of tropical rain belts. Small shifts in the positions of these rain belts may cause large local changes in precipitation. Changing seas surface temperatures (SST) are also important in controlling warm season rainfall variability and trends. For East Africa a temperature increase of 3.2 °C is predicted for 2080-2099, a precipitation increase of 7% and an increase in extreme wet events by 30% based on a 21 climate model average for the A1B scenario (IPCC, 2007). The increase in rainfall in East-Africa is robust across the ensemble of models. A total of 18 out of 21 models predict an increase in precipitation in this region (Figure 7).

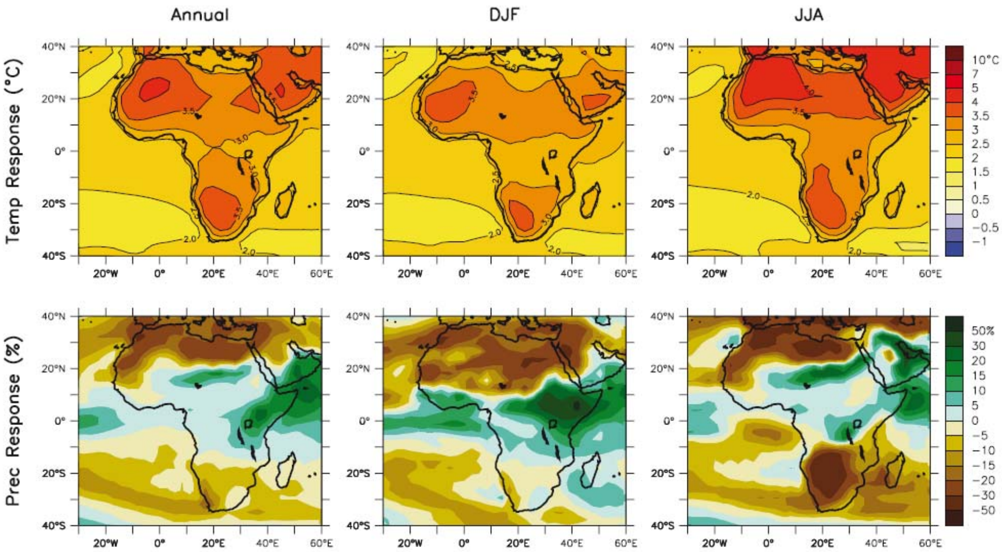


Figure 7 Temperature and precipitation changes over Africa from the MMD-A1B simulations. Top row: Annual mean, DJF and JJA temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Middle row: same as top, but for fractional change in precipitation. (Source: IPCC 2007)

3.3.2 Precipitation

Figure 8 shows the future precipitation projections for the station at Kakamega. During the control period between 1960 and 1990 the average annual precipitation equals 1510 mm. The projection for 2046-2065 is 1851 mm (+23%) and for 2080-2100 a total of 1979 mm (+31%) is projected. The most pronounced change is in January and February where for the period 2046-2065 an increase of almost 100% is projected compared to the control period. These are very considerable changes which are likely to have a serious hydrological impact. It is also interesting to see that there is a huge variation between the different scenarios in precipitation and it is therefore crucial to use data from multiple GCMs in climate change impact studies.

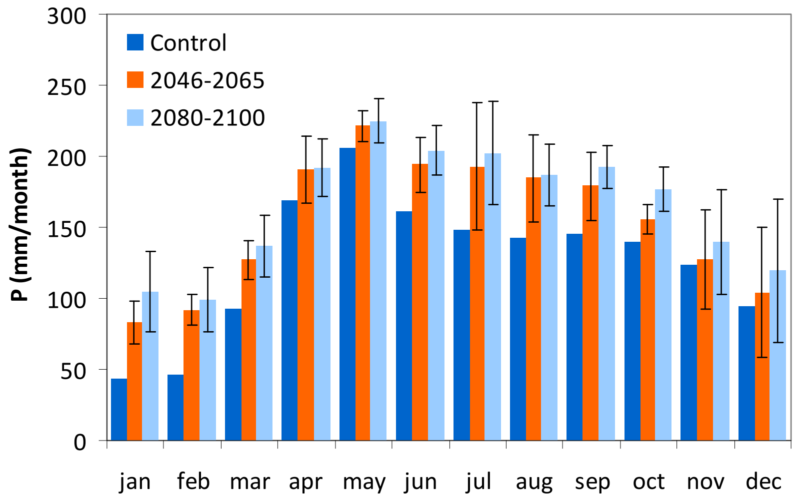


Figure 8 Projected monthly changes in precipitations for Kakamega. The control period is 1960-1990. The future projections are the multi-model average (MMA) of 6 GCMs. The error bars denote +/- one standard deviation between the 6 GCMs.

3.3.3 Temperature

The projected temperature increases are fairly constant throughout the year. For the period 2046-2065 a temperature increase of 2.0 °C is projected and for 2080-2100 an increase of 3.9 °C is foreseen.

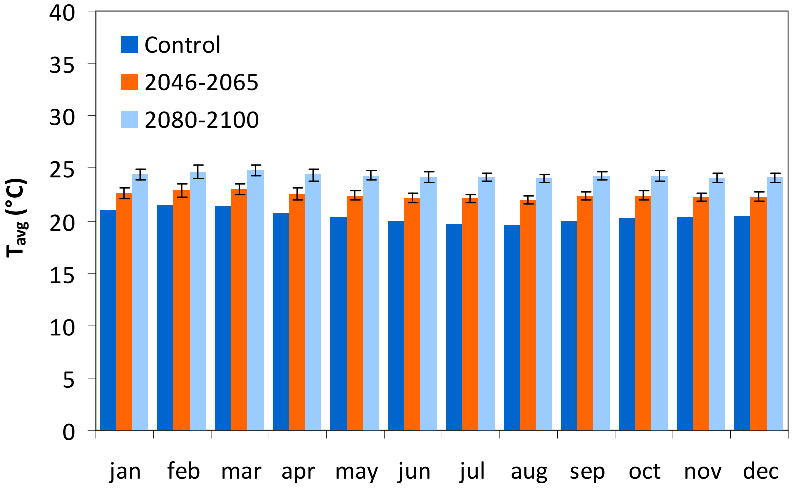


Figure 9 Projected monthly changes in temperature for Kakamega. The control period is 1960-1990. The future projections are the multi-model average (MMA) of 6 GCMs. The error bars denote +/- one standard deviation between the 6 GCMs.

3.3.4 Evapotranspiration

Reference evapotranspiration is important in assessing crop water demand and increase in temperature will also results in an increase in reference evapotranspiration. To make estimates of future changes in reference evapotranspiration use was made of the well-known Hargreaves equation:

$$ET_{ref} = 0.0023 \cdot R_e \cdot (T_{\max} - T_{\min})^{0.5} \cdot (T_{avg} + 17.8)$$

Where R_e is the extraterrestrial radiation, T_{max},T_{min}, T_{avg} are the maximum, minimum and average daily temperatures respectively.

Figure 10 shows the projected changes in reference evapotranspiration. For the period 2046-2065 the annual reference ET increases from 1632 mm y^{-1} to 1672 mm y^{-1}. In 2080-2100 ET_{ref} increases to 1745 mm y^{-1}. There are no clear differences between the different months.

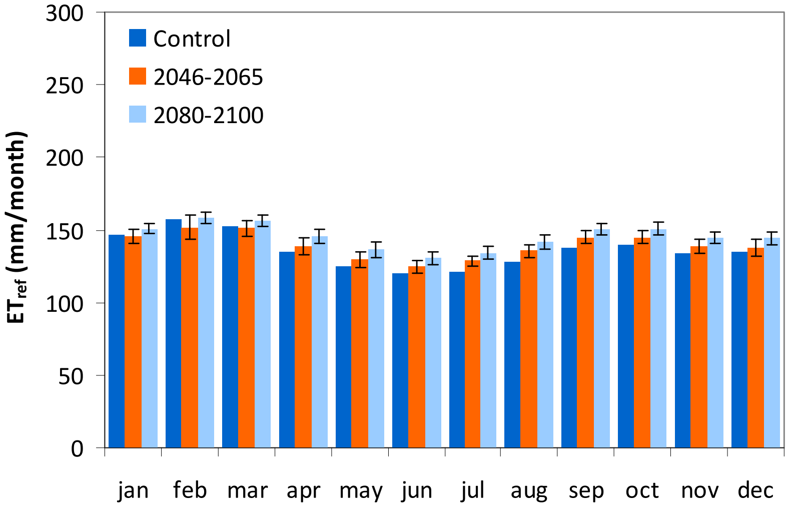


Figure 10 Projected monthly changes in reference evapotranspiration (Hargreaves) for Kakamega. The control period is 1960-1990. The future projections are the multi-model average (MMA) of 6 GCMs. The error bars denote +/- one standard deviation between the 6 GCMs.

3.4 Conclusions

Based on the analysis of historical data on temperature it is concluded that no significant temperature trend has been observed at four different locations across Kenya from 1979 to 2000. This is remarkable as it is to be expected that temperature trends would follow global warming trends. For precipitation a significant negative trend are observed at all stations. Some care is warranted with these conclusions as they are based on reanalysis data that are derived using a combination of model results and observations.

In the future the climate is very likely to change and all six GCMs show a consistent pattern in both precipitation and temperature. Kenya is one of the few African countries with an arid climate where a significant increase in precipitation is expected. For the period 2046-2065 an increase of 23% in annual precipitation is expected compare to the control period 1961-2000 and an increase of 31% in the period 2080-2100. Average temperature is expected to increase by 2°C and 3.9°C in 2046-2060 and 2080-2100 respectively. These temperature increases also yield a limited increase in reference evapotranspiration and thus in crop water demand.

4 Changes in water supply

4.1 Methodology

4.1.1 The Water Evaluation and Planning System (WEAP)

To quantify the water availability and assess how climate change will affect water supply to the Bunyala plains the WEAP model is recommended as the most appropriate tool. WEAP is short for Water Evaluation and Planning System. It is a computer tool for integrated water resources planning. It provides a comprehensive, flexible and user-friendly framework for policy analysis. WEAP is distinguished by its integrated approach to simulating water systems and by its policy orientation. WEAP is a laboratory for examining alternative water development and management strategies (SEI, 2005).

WEAP is operating on the basic principles of a water balance. The analyst represents the system in terms of its various supply sources (e.g. rivers, creeks, groundwater, and reservoirs); withdrawal, transmission and wastewater treatment facilities; ecosystem requirements, water demands and pollution generation. The data structure and level of detail may be easily customised to meet the requirements of a particular analysis, and to reflect the limits imposed by restricted data.

Operating on these basic principles WEAP is applicable to many scales; municipal and agricultural systems, single catchments or complex transboundary river systems. WEAP does not only incorporate water allocation but also water quality and ecosystem preservation modules. This makes the model suitable for simulating many of the fresh water problems that exist in the world nowadays.

WEAP applications generally include several steps. The study definition sets up the time frame, spatial boundary, system components and configuration of the problem. The Current Accounts, which can be viewed as a calibration step in the development of an application, provide a snapshot of the actual water demand, pollution loads, resources and supplies for the system. Key assumptions may be built into the Current Accounts to represent policies, costs and factors that affect demand, pollution, supply and hydrology. Scenarios build on the Current Accounts and allow one to explore the impact of alternative assumptions or policies on future water availability and use. Finally, the scenarios are evaluated with regard to water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables.

WEAP calculates a water and pollution mass balance for every node and link in the system. Water is dispatched to meet instream and consumptive requirements, subject to demand priorities, supply preferences, mass balance and other constraints. Point loads of pollution into receiving bodies of water are computed, and instream concentrations of polluting elements are calculated.

WEAP operates on a monthly time step, from the first month of the Current Accounts year through the last month of the last scenario year. Each month is independent of the previous month, except for reservoir and aquifer storage. Thus, all of the water entering the system in a month (e.g. head flow, groundwater recharge, or runoff into reaches) is either stored in an aquifer or reservoir, or leaves the system by the end of the month (e.g. outflow from end of river, demand site consumption, reservoir or river reach evaporation, transmission and return flow link losses). Because the time scale is relatively long (monthly), all flows are assumed to occur instantaneously. Thus, a demand site can withdraw water from the river, consume some, return the rest to a wastewater treatment plant that treats it and returns it to the river. This return flow is available for use in the same month to downstream demands (SEI, 2005b).

Each month the calculations (algorithms) follow this order (SEI, 2005):

1. Annual demand and monthly supply requirements for each demand site and flow requirement.
2. Runoff and infiltration from catchments, assuming no irrigation inflow (yet).
3. Inflows and outflows of water for every node and link in the system. This includes calculating withdrawals from supply sources to meet demand, and dispatching reservoirs. This step is solved by a linear program (LP), which attempts to optimise coverage of demand site and instream flow requirements, subject to demand priorities, supply preferences, mass balance and other constraints.
4. Pollution generation by demand sites, flows and treatment of pollutants, and loadings on receiving bodies, concentrations in rivers.
5. Hydropower generation.
6. Capital and operating costs and revenues.

Further details about WEAP are beyond the scope of this report, but can be found in various literature sources, and especially on the WEAP website and manuals (http://www.weap21.org/). Details on how WEAP compares to other modeling tools has been described elsewhere (Droogers et al., 2006)

4.2 General water supply

To build the WEAP model first the catchment boundaries were delineated based on the digital elevation model. The catchment was subdivided in sub-basins and the land use distribution within each sub-basin was determined using the AFRICOVER land use dataset (Table 4). The total area of the Nzoia catchment is 1,275,200 ha. The Bunyala irrigation scheme is located in sub-catchment 7.

Table 4 Land use distribution of sub-catchments (% of sub-catchment area)

Sub-catchment	Area (ha)	Rainfed agriculture	Irrigated agriculture	Forest	Rangeland	Wetland
1	153100	71	0	15	13	1
2	328800	73	0	19	6	1
3	11600	85	0	11	4	0
4	268900	86	0	10	2	2
5	252100	77	2	9	12	0
6	121000	67	0	18	14	0
7	139700	47	8	36	3	7

Each sub-basin provides water to the river network by rainfall-runoff. Runoff is modeled as excess precipitation after evapotranspiration has been subtracted. Evapotranspiration is calculated using potential evapotranspiration and the FAO crop factor method (Allen *et al.,* 1998).

The rainfall runoff catchments are represented as green nodes in Figure 11. All catchment supply water to the river system as runoff, but catchment c_11 and c_1 also have a water demand because part of the sub-basin is irrigated. Schematically this is visible though the green transmission link from the river to the catchment node. In the model the four major cities in the catchment (Kitale, Eldoret, Bungoma and Kakamega) are specified as water users. Urban water use is estimated by multiplying the number of inhabitants by an assumed daily water of 0.15 m^3. The catchment contains one small reservoir used for supplying drinking water to Eldoret. The capacity of the reservoir is 2 million m^3.

The WEAP model is forced by monthly precipitation estimate from the FEWS dataset. This is a raster based satellite derived precipitation estimate at a spatial resolution of 0.1° (~10 km). The average monthly precipitation for the period 2001 / 2007 is determined for each sub-basin and used as input for the model. Reference evapotranspiration is determined using the Hargreaves equation and local temperature data.

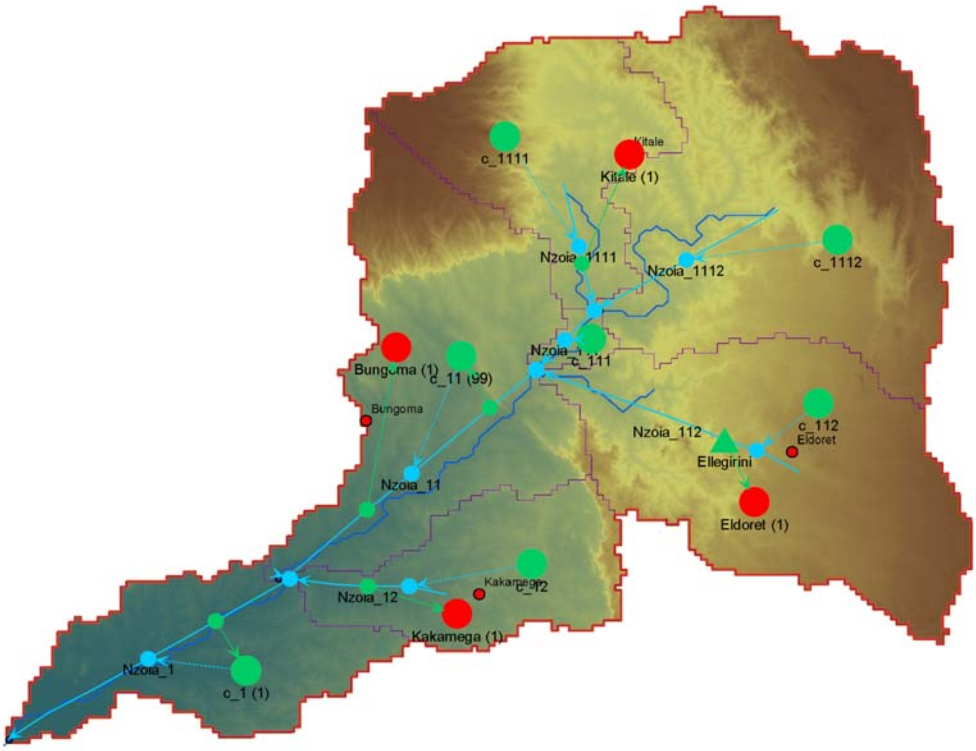


Figure 11 Schematic overview of the WEAP model

4.2.1 Current Climate

The model is calibrated (crop factors and effective precipitation parameters) using a dataset with observed daily discharges at the Nzoia bridge, which is about 10 km from Lake Victoria, from 1985 – 2006. For the overlapping period (2001-2006) the observed and WEAP simulated discharges is shown in Figure 12. With the exception of 2005 the simulated discharges match well with the observed discharges taken into account the relatively simple hydrological model concepts in WEAP (e.g. rainfall-runoff method and monthly time step). In 2005 there may be some inaccuracy in the FEWS rainfall estimates. The average observed discharge is 135.9 $m^3 s^{-1}$ and the average modeled discharge is 136.3 $m^3 s^{-1}$. The modeled discharge shows a somewhat larger variation but this can be attributed to the model concepts. It is concluded that the model can well be used to model effects of climate change on water availability in the catchment.

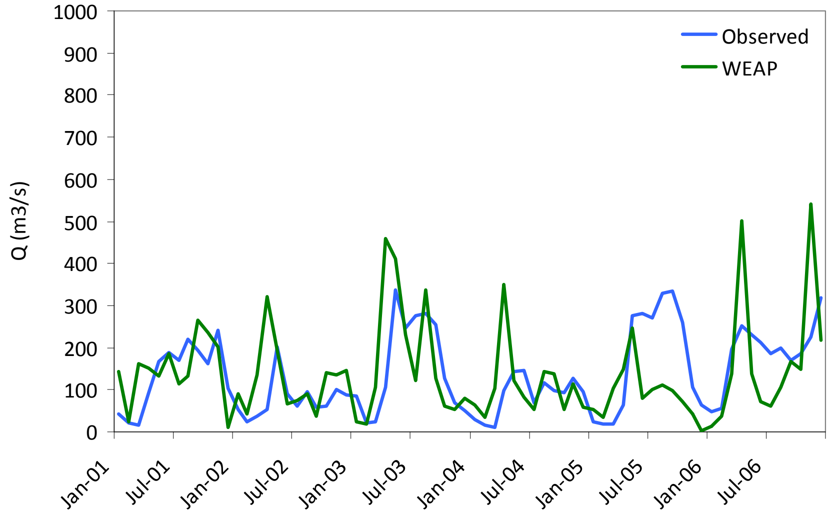


Figure 12: Observed and simulated discharges at the Nzoia bridge from 2001 to 2006.

An average discharge of 136.3 $m^3 s^{-1}$ corresponds to 337 mm / year over the entire catchment. Given an average annual precipitation of 1100 mm the runoff coefficient is 0.31, which is a normal value in a humid tropical climate. Figure 13 shows some hydrological characteristics based on the discharge record. The steepness of the flow duration curve is typical from a catchment that suffers from rain floods, e.g. during a small amount of time the discharge is extremely high. The monthly graph shows that January and February are the driest months and May the wettest. The monthly graph corresponds well with monthly precipitation (Figure 2).

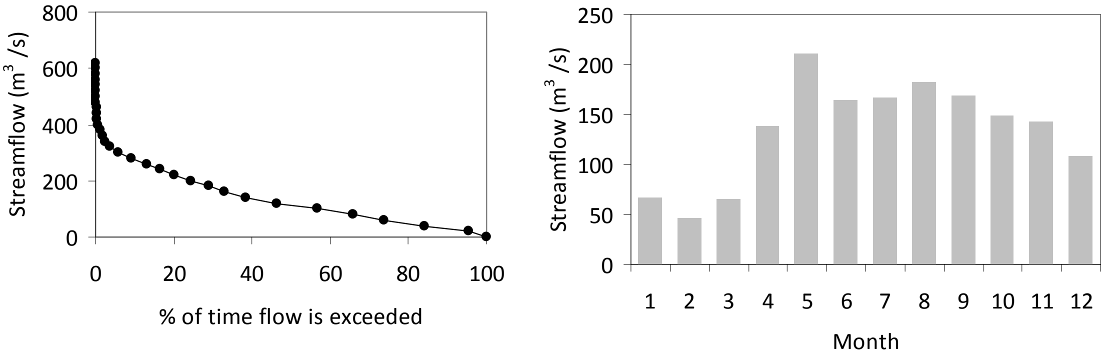


Figure 13: Flow duration curve and mean monthly discharge based on daily discharge data from 1985-2006

4.2.1.1 Climate change

First we analyze the effects of climate change (precipitation, temperature and reference ET) on the downstream water availability for the A2 scenario for 2050 and 2090. The average discharge in 2050 increases from 138.8 $m^3 s^{-1}$ to 189.0 $m^3 s^{-1}$ (+36%) and in 2090 to 209.8 $m^3 s^{-1}$ (+51%). Rainfall increases with 23% and 31% respectively and this illustrates the non-linear dynamic behaviors of rainfall-runoff processes, e.g. an increase in rainfall results in a more than proportional increase in discharge.

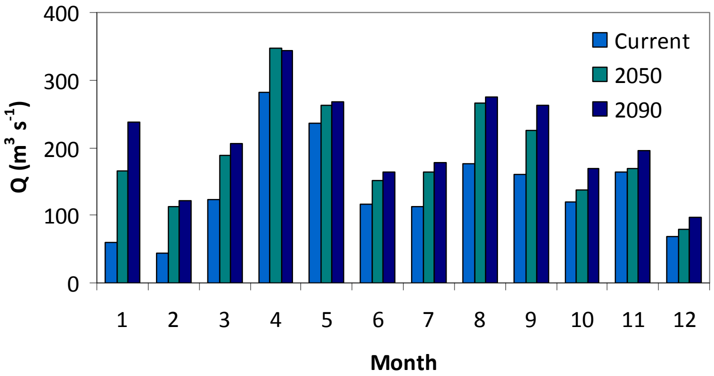


Figure 14: Monthly modeled flow in the Nzoia river in the current climate, in 2050 (A2 scenario) and 2090 (A2 scenario). Future scenarios are based on WEAP forcing by average climate data of the 6 GCMs.

Given the plans for extension of the Bunyala irrigation scheme it can be concluded that climate change yields a positive message as far as average water availability is concerned. In all months an increase in downstream discharge of the Nzoia River is likely and in combination with the increased local precipitation there is no reason to assume that water shortage is a critical limiting factor for the extension of the irrigation scheme.

shows the current and future water balances of the Nzoia river catchment. Currently a total of 73% of the precipitation is evaporated. Water consumption, defined as crop transpiration, by agriculture is 53%, and irrigated agriculture transpires only 1% of the total available water. Natural land covers such as forests and wetlands consume about 19% of the total available water. Another important conclusion is that the urban water use is negligible compared to the evaporation losses. A total of 27% leaves the basin as discharge to Lake Victoria. In 2050 the precipitation will increase by 24%. The rain fed land covers show slightly less but proportional increases. Water use by irrigated agriculture hardly increases due to a limited increase in reference ET and the fact that the actual ET is already close to the reference ET in the current climate. The net resultant of these changes is that the discharge increases significantly by 36%. In 2090 a similar pattern can be observed, precipitation has increased by 33% and discharge by 51%.

Table 5 Average annual water balance for the current climate, 2050 and 2090 for the Nzoia river catchment in million cubic meters, in % of precipitation and in % of current climate value.

	Current		2050			2090		
	10^6 m^3	%	10^6 m^3	% of P	% of current	10^6 m^3	% of P	% of current
Precipitation	15963	100%	19859	100%	124%	21296	100%	133%
ET rainfed agriculture	-8230	52%	-9893	50%	120%	-10445	49%	127%
ET irrigated agriculture	-237	1%	-246	1%	104%	-252	1%	106%
ET forests	-2030	13%	-2480	12%	122%	-2637	12%	130%
ET rangeland	-863	5%	-1012	5%	117%	-1058	5%	123%
ET wetland	-194	1%	-238	1%	123%	-253	1%	131%
Urban water use	-23	0%	-23	0%	100%	-23	0%	100%
Discharge	-4386	27%	-5968	30%	136%	-6628	31%	151%

4.3 Conclusions

The WEAP model is able to simulate river flow with acceptable accuracy during the reference period from 2001 and 2006. The Nzoia river catchment is the wettest catchment of Kenya and the flow duration curve is typical of a catchment that suffers from rain floods. The river discharge is lowest from January to March and relatively constant throughout the other months of the year with a peak in May. Rainfed agriculture is the largest water consumer (52% of total rainfall) in the catchment and urban water use is negligible. In total 27% of total rainfall is discharged into Lake Victoria.

The analysis with the water resources management tool WEAP reveals the hydrological impact of climate change. All scenarios show very significant increases in river discharge (36% in 2050 and 51% in 2090) and thus climate change will increase water availability which can provide important opportunities for both rain fed and irrigated agriculture. It is not likely that the planned expansion of the irrigation systems in the Bunyala plains will suffer from water shortage due too low flow conditions in the Nzoia river basin. River flow is the net resultant of all hydrological processes in the catchment and as such the relative increase is discharge is higher than the precipitation increase. The other components of the water balance increase proportionally.

5.1 Flood frequency analysis

In Figure 15 the maximum annual stream flow from 1985 to 2006 is shown. There are no real trends in maximum stream flow. The highest peak was in 1985 when a discharge was observed of 600 m^3 s^{-1} Based on this dataset a flood frequency analysis was performed.

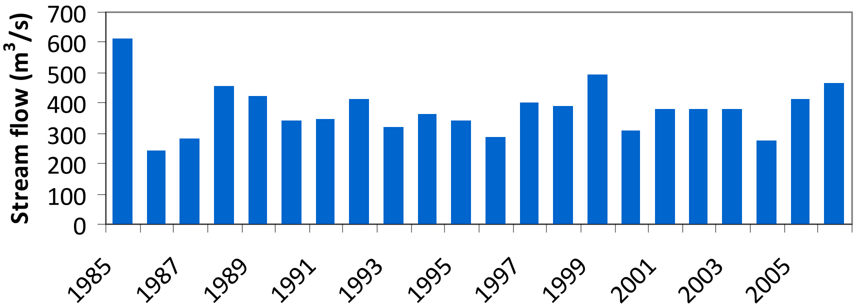


Figure 15 Maximum annual stream flow

Several distributions were tested and the Generalized Extreme Value (GEV) distribution was selected to best fit the extreme value distribution of the annual discharges of the Nzoia river. Figure 16 shows that the chosen distribution matches the observed data well. Once the distribution has been selected it can be determined which extreme discharge belongs to a certain recurrence time.

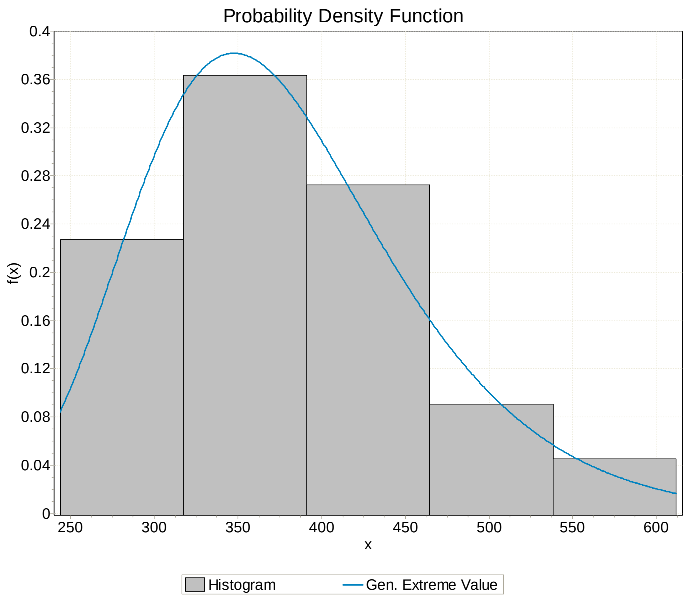


Figure 16 The GEV distribution fitted to the Nozia river annual maximum discharge data

For the future climate change scenario an estimate was made of the increase in maximum annual discharge. Given the high non-linear behavior of rainfall-runoff processes it is not possible to derive this increase by using projected increase in rainfall. Therefore another approach was adopted. A linear relationship is observed between average monthly discharge and maximum monthly discharge. Since the WEAP modeling provides the increase in average monthly discharge the same relative increase in maximum discharge per month is used to generate a future time series of extreme discharges. The relative monthly increase in average discharge (%) is superimposed on the daily time series of observed discharges and subsequently the flood frequency analysis is repeated. The results are shown in Table 6. Although the results are indicative, very significant flooding problems are to be expected in the future unless adaptation measures are taken. A peak discharge that currently occurs only once in 30 year will in 2050 occur more often than once in 5 years and a peak discharge that occurs every two year in 2090 occurs once in 30 years in the current climate. Taken into account that large areas are currently flooded with a frequency higher than 1:5 years the future looks grim, unless far-fetching measures are taken. The results should however be interpreted with care as the assumption of a linear relation between average and maximum monthly discharge may not persist under future climate scenarios. It is recommended to perform a flood modeling study using tailored software such as the HEC-RAS package developed by the US Army Corp of Engineers. This is however beyond the scope of the current study.

Table 6 Extreme discharges at different recurrence periods for the current climate, 2050 and 2090

T (year)	Q current (m^3/s)	Q 2050 (m^3/s)	Q 2090 (m^3/s)
2	368	485	540
5	446	636	760
10	490	751	948
15	510	823	1071
20	528	876	1167
30	554	953	1313

5.1.1 Flood extent delineation

We estimate the extent of the flooding by assuming that the dyke is 3 meters high and the river bed is 50 meters wide. Using these data the flow velocity under the current climate at a discharge of 446 m^3/s at the location of the dyke break equals 2.97 m/s. If we assume the velocity is more or less constant we can estimate the increase in water depth when the discharge increases to 636 m^3/s (Table 6). By using a high resolution digital elevation model derived from the ASTER satellite with a spatial resolution of 30m[1] it is possible to make a rough estimate of the flood extent as well as the inundation depth under the current climate and in the future (Figure 17). Under the current climate a total area of 18943 ha is inundated with an average inundation depth of 4.9 m., while in 2050 a total area of 21335 ha inundates once every five year with an average inundation depth of 5.4 m.

[1] http://www.gdem.aster.ersdac.or.jp/

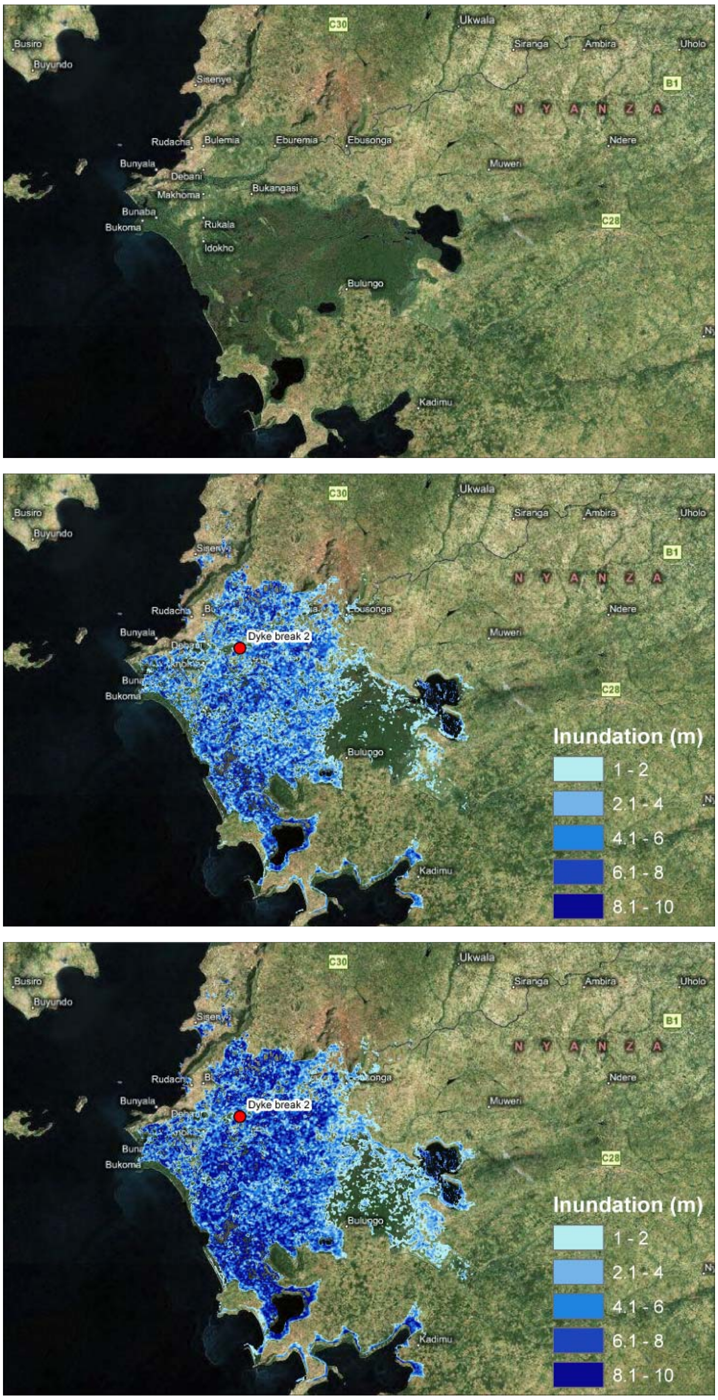


Figure 17 Estimate flood depth for a recurrence time of 5 years for the current climate (middle maps) and the 2050 climate (bottom map). The top figure shows an overview of the area.

5.2 Conclusions

The largest threat of climate change in the Bunyala plains is flooding. Currently flooding is already a big problem on the Bunyala plains with regular dike breaks resulting in the loss of infrastructure and the displacement of thousands of people. Based on the quick scan of this study very significant increase in peak discharges are to be expected. It is estimated that a flood that occurs once every 10 years now will occur once every two years in 2050 and a flood that occurs very 25 years now will occur once every 2 years in 2090. Both the flood extent and inundation depth are likely to increase. Some caution is warranted with these conclusions as a simplified method has been used and it is recommended to develop a flooding model for future evaluation. However there is no doubt that flooding is the most serious problem for the future and any planned developments and extensions of irrigated agriculture should be preceded by a thorough assessment of the required dike improvement to acceptable security standards to protect both people and infrastructure.

6 Impact and Opportunities of Climate Change on Agriculture on the Bunyala plains

6.1 Introduction

Potential impacts of climate change on world food supply have been estimated in several studies (Parry et al., 2004). Results show that some regions may improve production, while others suffer yield losses. This could lead to shifts of agricultural production zones around the world. Furthermore, different crops will be affected differently, leading to the need for adaptation of supporting industries and markets. Climate change may alter the competitive position of countries with respect, for example, to exports of agricultural products. This may result from yields increasing as a result of altered climate in one country, whilst being reduced in another. The altered competitive position may not only affect exports, but also regional and farm-level income, and rural employment.

In order to evaluate the effect of climate change on crop production and to assess the impact of potential adaptation strategies models are used frequently (Aerts and Droogers, 2004). The use of these models can be summarized as: (i) better understanding of water-food-climate change interactions, and (ii) exploring options to improve agricultural production now and under future climates. Some of the frequently applied agricultural models are:

- CropWat
- AquaCrop
- CropSyst
- SWAP/WOFOST
- CERES
- DSSAT
- EPIC

Each of these models is able to simulate crop growth for a range of crops. The main differences between these models are the representation of physical processes and the main focus of the model. Some of the models mentioned are strong in analysing the impact of fertilizer use, the ability to simulate different crop varieties, farmer practices, etc. However, for the project it is required to use models with a strong emphasis on crop-water-climate interactions. The three models that are specifically strong on the relationship between water availability, crop growth and climate change are CropWat, AquaCrop and SWAP/WOFOST. Moreover, these three models are in the public domain, have been applied world-wide frequently, and have a user-friendly interface (Figure 18). Based on previous experiences it was selected to use AquaCrop as it has:

- limited data requirements
- a user-friendly interface enabling non-specialits to develop scenarios
- focus on climate change, CO_2, water and crop yields
- flexibility in expanding level of detail.

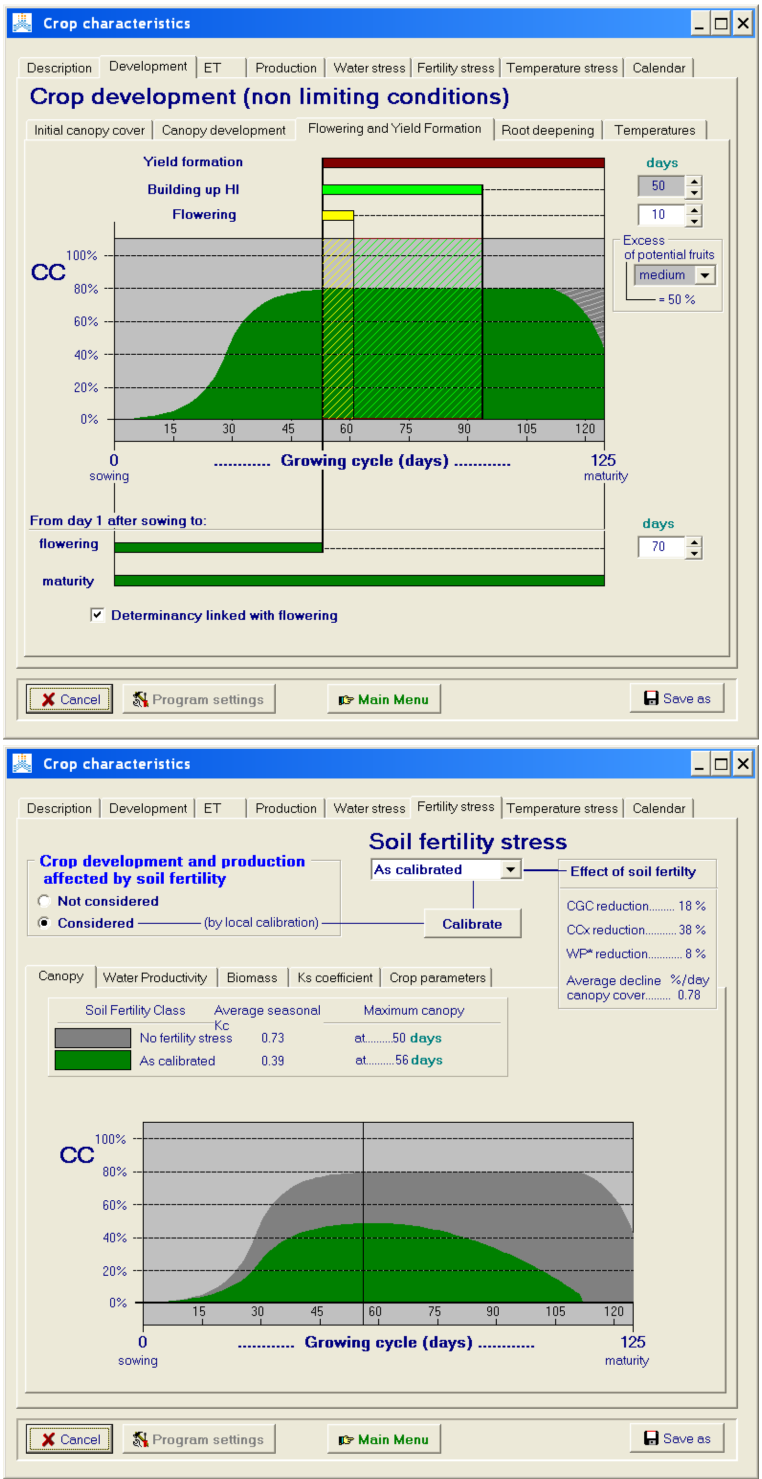


Figure 18. Typical examples of input screen of AquaCrop: crop development (top) and soil fertility stress (bottom).

6.2 AquaCrop

AquaCrop is the FAO crop-model to simulate yield response to water. It is designed to balance simplicity, accuracy and robustness, and is particularly suited to address conditions where water is a key limiting factor in crop production. AquaCrop is a companion tool for a wide range of users and applications including yield prediction under climate change scenarios. AquaCrop is a completely revised version of the successful CropWat model. The main difference between CropWat and AquaCrop is that the latter includes more advanced crop growth routines.

AquaCrop includes the following sub-model components: the soil, with its water balance; the crop, with its development, growth and yield; the atmosphere, with its thermal regime, rainfall, evaporative demand and CO2 concentration; and the management, with its major agronomic practice such as irrigation and fertilization. AquaCrop flowchart is shown in Figure 19.

The particular features that distinguishes AquaCrop from other crop models is its focus on water, the use of ground canopy cover instead of leaf area index, and the use of water productivity values normalized for atmospheric evaporative demand and of carbon dioxide concentration. This enables the model with the extrapolation capacity to diverse locations and seasons, including future climate scenarios. Moreover, although the model is simple, it gives particular attention to the fundamental processes involved in crop productivity and in the responses to water, from a physiological and agronomic background perspective.

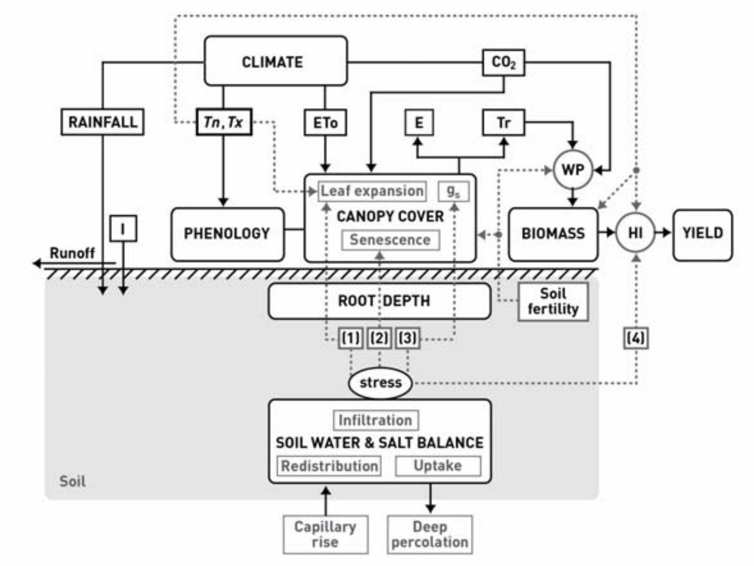


Figure 19. Main processes included in AquaCrop.

6.2.1 Theoretical assumptions

The complexity of crop responses to water deficits led to the use of empirical production functions as the most practical option to assess crop yield response to water. Among the empirical function approaches, FAO Irrigation & Drainage Paper nr 33 (Doorenbos and Kassam, 1979) represented an important source to determine the yield response to water of field, vegetable and tree crops, through the following equation:

$$\left(\frac{Y_x - Y_a}{Y_x}\right) = k_y\left(\frac{ET_x - ET_a}{ET_x}\right) \qquad \text{Eq. 1}$$

where Y_x and Y_a are the maximum and actual yield, ET_x and ET_a are the maximum and actual evapotranspiration, and k_y is the proportionality factor between relative yield loss and relative reduction in evapotranspiration.

AquaCrop evolves from the previous Doorenbos and Kassam (1979) approach by separating (i) the ET into soil evaporation (E) and crop transpiration (Tr) and (ii) the final yield (Y) into biomass (B) and harvest index (HI). The separation of ET into E and Tr avoids the confounding effect of the non-productive consumptive use of water (E). This is important especially during incomplete ground cover. The separation of Y into B and HI allows the distinction of the basic functional relations between environment and B from those between environment and HI. These relations are in fact fundamentally different and their use avoids the confounding effects of water stress on B and on HI. The changes described led to the following equation at the core of the AquaCrop growth engine:

$$B = WP \cdot \Sigma Tr \qquad \text{Eq. 2}$$

where Tr is the crop transpiration (in mm) and WP is the water productivity parameter (kg of biomass per m2 and per mm of cumulated water transpired over the time period in which the biomass is produced). This step from Eq. 1.1 to Eq. 1.2 has a fundamental implication for the robustness of the model due to the conservative behavior of WP (Steduto et al., 2007). It is worth noticing, though, that both equations are different expressions of a *water-driven growth-engine* in terms of crop modeling design (Steduto, 2003). The other main change from Eq. 1.1 to AquaCrop is in the time scale used for each one. In the case of Eq. 1.1, the relationship is used seasonally or for long periods (of the order of months), while in the case of Eq. 1.2 the relationship is used for daily time steps, a period that is closer to the time scale of crop responses to water deficits.

The main components included in AquaCrop to calculate crop growth are Figure 20:

- Atmpsohere
- Crop
- Soil
- Field management
- Irrigation management

These five components will be discussed here bullet-wise. Details can be found in the AquaCrop documentation (Raes et al., 2009)

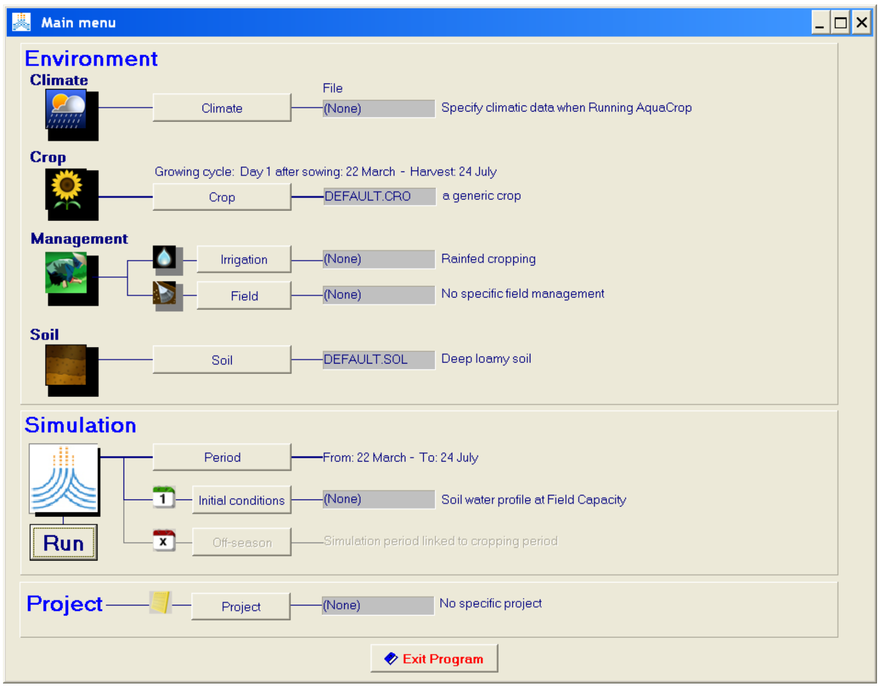


Figure 20. Overview of AuqaCrop showing the most relevant components.

6.2.2 Atmosphere

AquaCrop requirements for weather data include the following five parameters:

- daily minimum air temperatures
- daily maximum air temperatures
- daily rainfall
- daily evaporative demand of the atmosphere expressed as reference evapotranspiration (ET_o)
- mean annual carbon dioxide concentration in the bulk atmosphere

The reference evapotranspiration (ET_o) is, in contrast to CropWat, not calculated by AquaCrop itself, but is a required input parameter. This enables the user to apply whatever ETo method based on common practice in a certain region and/or availability of data. From the various options to calculate ETo reference is made to the Penman-Monteith method as described by FAO (Allen *et al.*, 1998). The same publication makes also reference to the Hargreaves method in case of data shortage. A companion software program (ETo calculator) based on the FAO56 publication might be used if preference is given to the Penman-Monteith method.

AquaCrop calculations are performed always at a daily time-step. However, input is not required at a daily time-step, but can also be provided at 10-daily or monthly intervals. The model itself interpolates these data to daily time steps. The only exception is the CO_2 levels which should be provided at annual time-step and are considered to be constant during the year.

6.2.3 Crop

AquaCrop considers five major components and associated dynamic responses which are used to simulate crop growth and yield development:

- phenology
- aerial canopy
- rooting depth
- biomass production
- harvestable yield

As mentioned earlier, AquaCrop strengths are on the crop responses to water stress. If water is limiting this will have an impact on the following three crop growth processes:

- reduction of the canopy expansion rate (typically during initial growth)
- acceleration of senescence (typically during completed and late growth)
- closure of stomata (typically during completed growth)

Finally, the model has two options for crop growth and development processes:

- calendar based: the user has to specify planting/sowing data
- thermal based on Growing Degree Days (GDD): the model determines when planting-sowing starts.

6.2.4 Soil

AquaCrop is flexible in terms of description of the soil system. Special features:

- Up to five horizons
- Hydraulic characteristics:
    - hydraulic conductivity at saturation
    - volumetric water content at saturation

    - field capacity
    - wilting point
- Soil fertility can be defined as additional stress on crop growth influenced by:
    - water productivity parameter
    - the canopy growth development
    - maximum canopy cover
    - rate of decline in green canopy during senescence.

AquaCrop separates soil evaporation (E) from crop transpiration (Tr). The simulation of Tr is based on:

- Reference evapotranspiration
- Soil moisture content
- Rooting depth

Simulation of soil evaporation depends on:

- Reference evapotranspiration
- Soil moisture content
- Mulching
- Canopy cover
- Partial wetting by localized irrigation
- Shading of the ground by the canopy

6.2.5 Field management

Characteristics of general field management can be specified and are reflecting two groups of field management aspects: soil fertility levels and practices that affect the soil water balance. In terms of fertility levels one can select from pre-defined levels (non limiting, near optimal, moderate and poor) or specify parameters obtained from calibration. Field management options influencing the soil water balance that can be specified in AquaCrop are mulching, runoff reduction and soil bunds.

6.2.6 Irrigation management

Simulation of irrigation management is one of the strengths of AquaCrop with the following options:

- rainfed-agriculture (no irrigation)
- sprinkler irrigation
- drip irrigation
- surface irrigation by basin
- surface irrigation by border
- surface irrigation by furrow

Scheduling of irrigation can be simulated as

- Fixed timing
- Depletion of soil water[1]

Irrigation application amount can be defined as:

- Fixed depth
- Back to field capacity

[1] Not yet available in the latest version of AquaCrop (version 3.0)

6.2.7 Climate change

The impact of climate change can be included in AquaCrop by three factors: (i) adjusting the precipitation data file, (ii) adjusting the temperature data file, (iii) impact of enhanced CO_2 levels. The first two options are quite straightforward and require the standard procedure of creating climate input files in AquaCrop. Impact of enhanced CO_2 levels are calculated by AquaCrop itself. AquaCrop uses for this the so-called normalized water productivity (WP*) for the simulation of aboveground biomass. The WP is normalized for the atmospheric CO_2 concentration and for the climate, taking into consideration the type of crop (e.g. C3 or C4). The C4 crops assimilate carbon at twice the rate of C3 crops.

6.3 Input parameters

Rice is the most important crop currently grown in the Bunyala irrigation scheme. A total of 304 hectares is in use and every year two crops are cultivated: one crop cycle from February to July and one from September to December. The farmers use both ammonium suplhate (250 kg / ha) and ureum (125 kg / ha) as fertilizer. Carbofuran is used as pesticide on the rice seedlings. The average yield is 5535 kg ha^{-1} and the market price is 0.41$ kg^{-1}.

AquaCrop has been set up for Bunyala site for three conditions:

- Reference = current conditions
- Impact = climate change impact at 2050, without adaptation measures
- Adaptation = impact of climate change at 2050, with adaptation measures. Three adaptation measures were evaluated:
    - transition from 2 crops to 3 crops a year
    - changes from irrigated to rainfed rice
    - changes from irrigated rice to rainfed maize

For the specific case of Bunyala a summary of the most important input parameters for the reference case are:

- Climate as described in the previous chapter.
- Crop
    - Standard rice crop
    - Transplanting dates (double cropping): 1-Feb and 1-Sep
- Soil
    - Deep uniform clay loam profile, with puddling layer at 30 cm depth
    - Soil fertility condition set as “non limited”
- Irrigation
    - First growing season: every 7 days 50 mm
    - Second growing season: every 7 days 30 mm

The impact of climate change for the year 2050 has been included in the model by:

- Changes in precipitation according to IPCC scenarios derived from the CCE.
- Changes in temperature according to IPCC scenarios derived from the CCE.
- Changes in reference evapotranspiration according to IPCC scenarios derived from the CCE.
- Enhanced CO_2 levels from 370 ppm (2000) to 500 ppm (2050). The IPCC projections for 2100 vary between 600 and 850 ppm.

AquaCrop has a limitation that only one growing season can be evaluated. In Bunyala it is common practice of having two crops growing in one year and therefore for each growing season a separate model was setup.

6.4 Results

6.4.1 Reference

AquaCrop has many options to present output: graphs, daily output, cumulative output, export to a file etc. A typical example of output in a graphical way is shown in Figure 21. The following output files are created by AquaCrop that can subsequently be being used in other programs, like spreadsheets, to analyze and or plot results. The output files contain daily data of:

- Crop development and production;
- Soil water content at various depths of the soil profile;
- Soil water content in the root zone;
- Various parameters of the soil water balance;
- Net irrigation water requirement.

The reference case for Bunyala reflects the current situation including average climate conditions, crop and farm management. Data for the reference conditions have been described in the previous sections and here output will be discussed. Figure 22 shows on a daily base the main terms of the water balance as well as the crop development as simulated using AquaCrop. The figure shows the irrigation management practice of 50 mm every 7 days during the first growing season (February to May) and 30 mm every 7 days during the second growing season (September to December). These different irrigation application amounts follow the normal climate with lower rainfall at the beginning of the year compared to the end of the year.

Figure 22 indicates that part of the irrigation water is not used to support crop growth but is drained. Based on this figure one could claim that less water could be provided for irrigation, but within rice systems drainage is an unavoidable process as standing water on the fields is required for a good yield. However, at the end of the first growing season, in May, also some runoff occurs as a result of irrigation. A reduction or a somewhat more responsive irrigation application would be normal practice, but irrigation scheduling is not yet implemented in the AquaCrop model so far (version 3.0).

The development of biomass and harvestable yield is also presented in Figure 22. Biomass growth and grain development can be observed in the figure. Total yield for both seasons are almost similar at the level of almost 7000 kg per ha. The average observed yield is somewhat lower at around 5500 kg per ha. This difference can be explained by the following reasons. First of all, diseases are not included in the AquaCrop model. In reality for some years and some fields crop yields were reduced because of diseases and pests. Second, it was assumed that soil fertility was not limiting as farmers provided quite some fertilizer to their crops. However, it might be that in reality some nutrient stresses might occur. Finally, the rice crop variety included in the model was a quite high-yielding one as developed at the International Rice Research Institute. It might be that farmers are using somewhat less developed varieties with lower production potentials.

It has been proven, however, that relative model accuracy (e.g. comparing reference conditions to scenarios) is much higher than absolute model accuracy (e.g. comparing model to observations) (Droogers at al., 2008). Therefore, it was decided that the model can be used for scenario analysis.

6.4.2 *Impact climate change*

Based on the reference case climate change impact assessment was undertaken, by using exactly the same model and altering climate conditions. Precipitation, temperature, reference evapotranspiration and CO_2 levels were adjusted to the conditions for around 2050. The AquaCrop model shows that drainage and runoff will increase as a result of higher precipitation levels (Figure 23). Also higher temperatures will induce higher evapotranspiration demands. However, elevated CO_2 levels will have a substantial impact on crop growth and it is expected that yields will increase substantially (Table 7).

One could argue that because of the expected increase in rainfall and the positive impact of CO_2 on crop growth adaptation to climate change is not necessary with respect to crop production. However, other parts of Kenya will suffer from more prolonged droughts so an increase in crop production is very beneficial for the country as a whole. Also, it is expected that year-to-year variation in rainfall will increase due to climate change and therefore higher crop production is required under normal conditions in order to have sufficient stock when low rain conditions occur. Therefore, it was decided to test the following two adaptation strategies:

- Change to rainfed rice
- Change to three crops a year

6.4.3 *Rainfed rice*

Since precipitation is expected to increase by over 20% the option of changing completely to rainfed rice was explored. Although the pervious chapter showed that sufficient water will be available in the river, the option of reducing irrigation might be attractive for two reasons. First of all, this option will save energy costs and will make agriculture more profitable. Second, if rainfed rice is feasible this opens the opportunity to expand the rice production even outside the irrigation area.

Table 7 indicates that stopping irrigation entirely is not an option as increase in rainfall is still not sufficient for rainfed rice production. Interesting is the large difference between the two growing seasons. Yields will go down to zero for the first season as there will be a period where the rice crop will die as conditions are too dry. For the second growing season yields will be at the same level as obtained under normal irrigation conditions. It was therefore tested if a limited amount of irrigation (10 mm every 7 days) during the first growing season would be sufficient. This small irrigation application is also not sufficient to produce a reasonable yield (Table 7). It was therefore also evaluated whether 30 mm every 7 days would be sufficient to have optimal yield during the first growing season. The model indicated this would be sufficient as yields will be 8.7 ton per hectare.

Since completely shifting to rainfed rice production is not feasible the area still depends on irrigation infrastructure. Since water is sufficiently available in the region reducing irrigation applications is not really desired. Only if complete rainfed production would be possible, so irrigation infrastructure is not required anymore, big economic and managerial benefits can be expected.

It can be therefore concluded that under future climate change conditions despite an increase in precipitation, irrigation is still required for rice production.

6.4.4 Three crops

Since water is not the limiting factor in the region one could consider changing from two crops to three crops a year. Current rice production is based on a 104 day cultivar. However, given time required for field preparation a shorter variety should be introduced with a growing season of 90 days. Yield of this short duration variety might be however somewhat lower, but this might be compensated by having three yields in stead of two.

In Figure 24 the water balance terms and crop growth indicators for this scenario are shown. Irrigation under this scenario is limited to 13 times 35 mm for each growing season. Individual yields for the three crops per season are somewhat lower compared to the two crops option and are in the range between 6300 and 6600 kg per hectare. However, since three crops can be grown total annual yields are still higher. A socio-economic analysis should indicate whether this is still recommend scenario, as more costs are involved in three crops compared to two crops.

At this stage also the linkage with the WEAP analysis should be made to explore whether sufficient water will be available to make a transition from two to three crops a year. Three options will be evaluated:

1. Is there sufficient water available and pumping capacity to irrigate the current extent of 304 ha?
2. Is there sufficient water available and pumping capacity to irrigate the total irrigation scheme of 2428 ha?
3. What is the maximum area that might be put under rice cultivation assuming three crops a year?

1) Total annual irrigation requirement is 1170 mm (Table 7). Converting this to cubic meters using the current extent of 304 ha provides 3.6 MCM ~ 0.1 $m^3\ s^{-1}$. Given the water availability of 5968 MCM in the year 2050 and the current pump capacity of 0.6 $m^3\ s^{-1}$, no problems will be foreseen.
2) Similar as situation 1) but now for the 2428 ha total irrigation scheme, total water requirements are 28.4 MCM ~ 0.9 $m^3\ s^{-1}$. This indicates that sufficient water will be available but that pump capacity should be expanded.

3) The analysis on total water availability in the river indicated 5968 MCM annually. This amount would indicate that about 50,000 ha can be irrigated assuming three crops a year. However, the most critical month is February where average expected flow is about 50 $m^3\ s^{-1}$ and irrigation requirements are 150 mm. Using this figures a total of 80,000 ha could be irrigated. This is however a somewhat positive figure as one should rely more on the 80% reliability of water availability rather than on the average flow projected. If we consider therefore the probability analysis as presented in the previous chapter one could expect to have at leats 20 $m^3\ s^{-1}$ in February in 80% of the years in 2050. Given this figure still sufficient water will be available to irrigate 30,000 ha.

Table 7. Indicators presenting impact and adaptation of climate change.

	Reference	CC	CC no irr	CC 10 irr	CC 30 irr	3-crops
Crop Yield May (ton / ha)	6.8	9.1	0.0	3.0	8.7	N/A
Crop Yield Nov (ton / ha)	6.6	9.1	9.3	9.3	9.3	N/A
Crop Yield total (ton/ha)	13.4	18.2	9.3	12.3	18.1	19.3
Irrigation (mm/year)	1200	1200	0	150	150	1170
Precipitation (mm/year)	1507	1855	1855	1855	1855	1855
ET (mm/year)	1663	1754	1703	1703	1703	1724

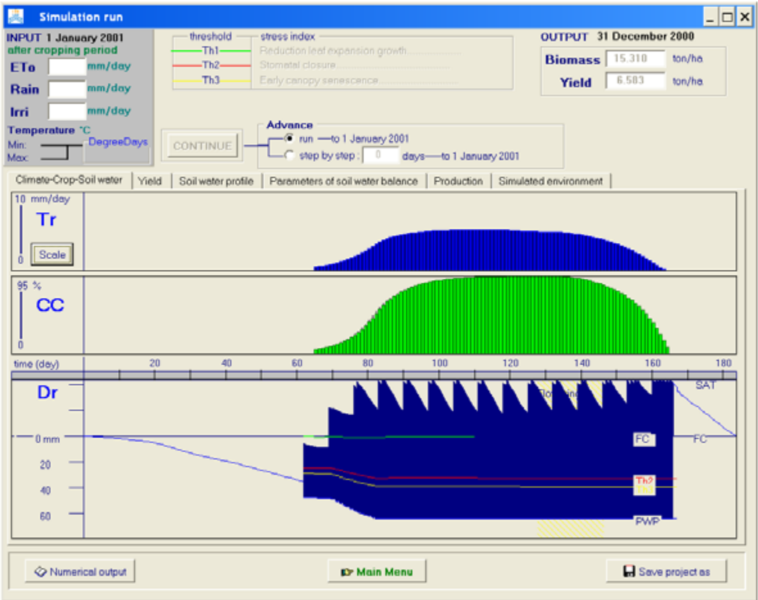
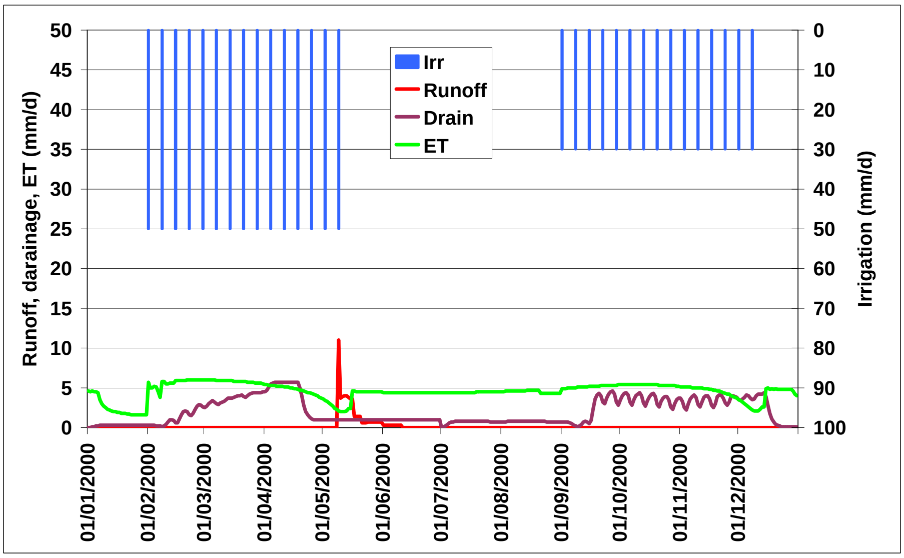


Figure 21. Typical output of AquaCrop.



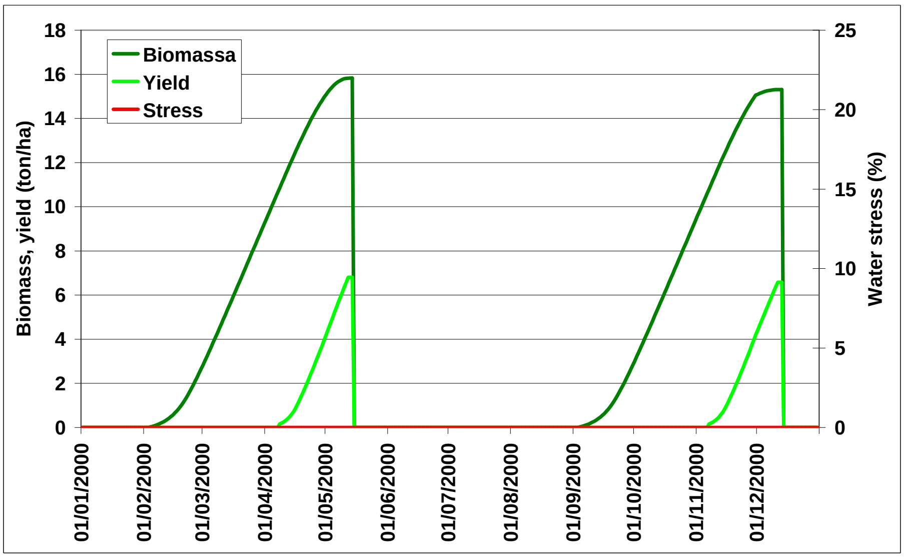
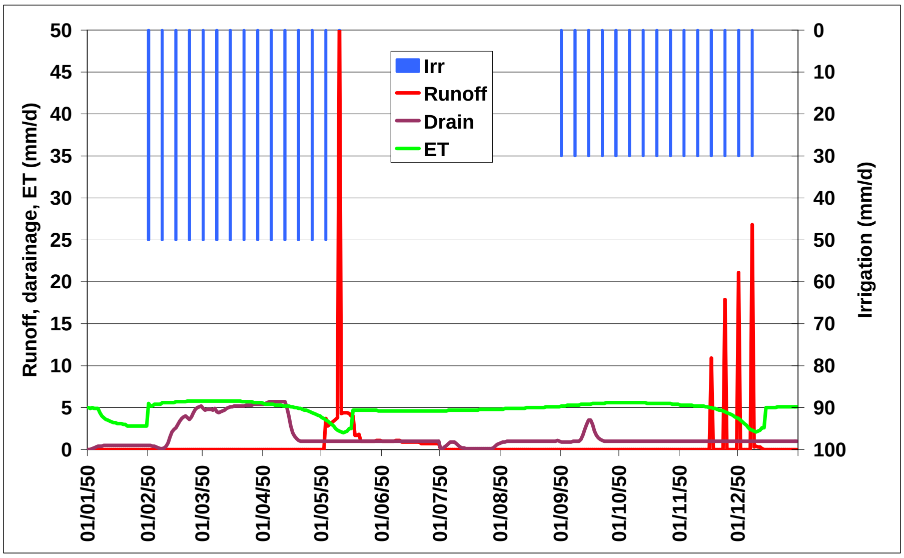


Figure 22. Output AquaCrop for the reference situation: soil water (top) and crop growth (bottom).



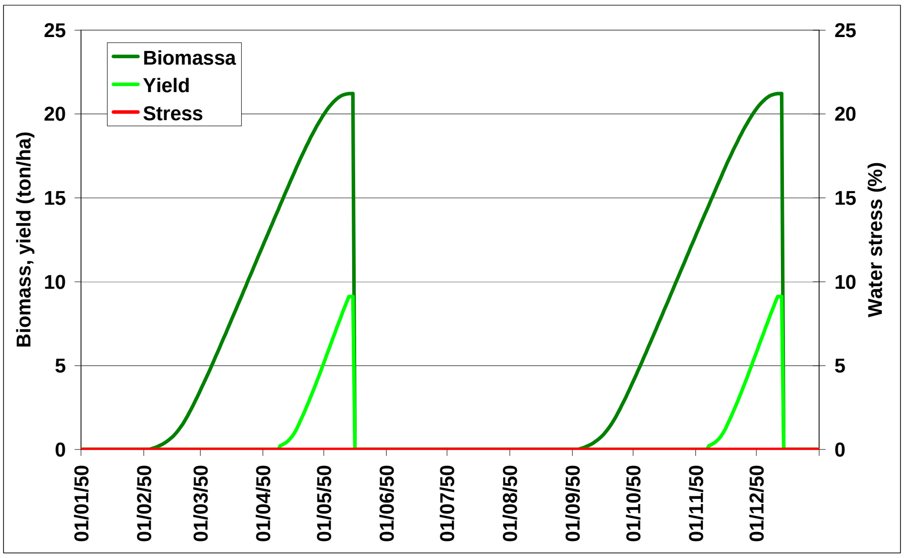
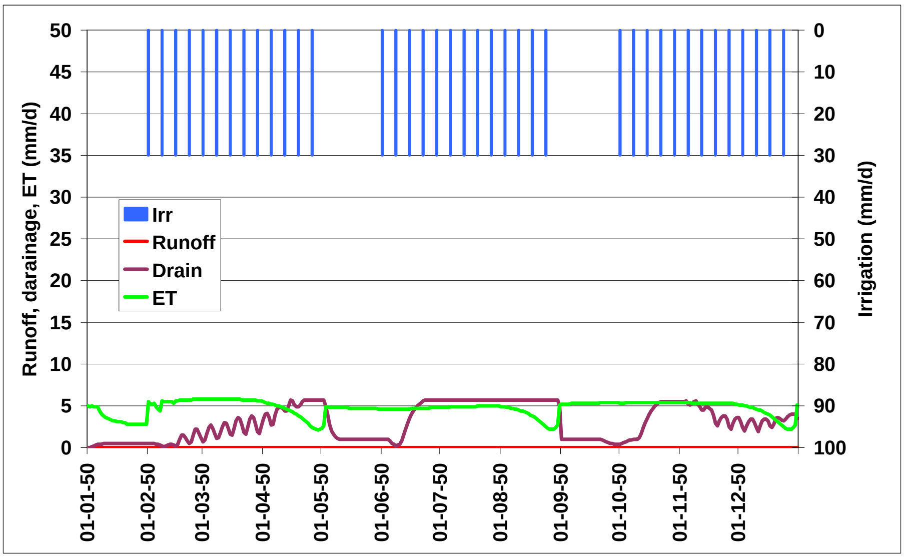


Figure 23. Output AquaCrop for the climate change scenario: soil water (top) and crop growth (bottom).



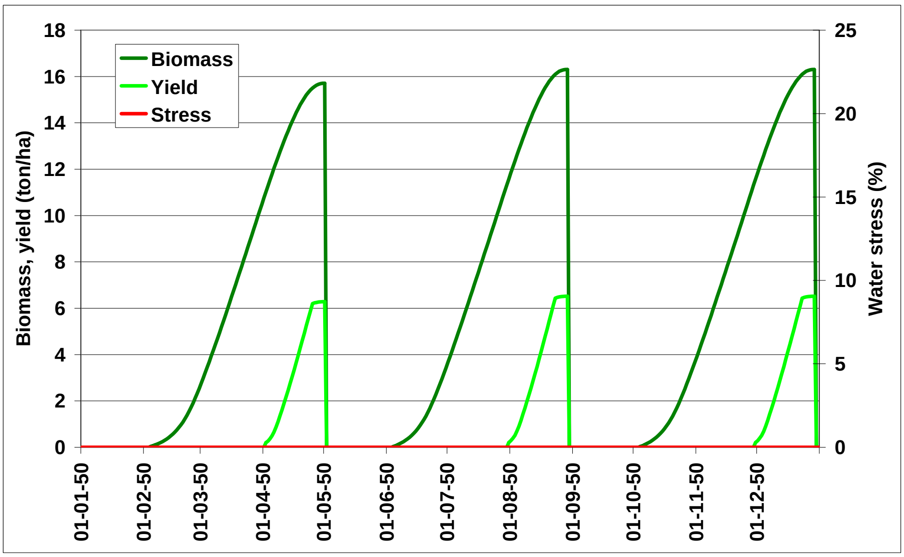


Figure 24. Output AquaCrop for the adaptation to change from two to three growing seasons: soil water (top) and crop growth (bottom).

6.5 Conclusions

AquaCrop can be considered as the ultimate tool to undertake a swift yet comprehensive impact and adaptation assessment to climate change for crop production. The number of scenarios that can be analysed is virtually unlimited and is mainly restricted by quality of data. In this chapter a limited number of scenarios is evaluated to focus on the most relevant ones and to demonstrate the use of AquaCrop. Obviously, if real investments are considered a more detailed analysis is required where the focus should be on obtaining additional data, further calibration of the model and intensified contacts with farmers and water managers.

Based on the analysis it is very clear that given the fact that water is abundant there is sufficient scope for expanding the irrigated area. The analysis revealed also that a complete shift to rain fed rice is even under the expected increase in rainfall not feasible. This can be mainly attributed to the anticipated crop failure during the first season. Finally it was concluded that the impact of the combined effect of CO_2 fertilization, and the increase in rainfall, more rice can be produced under climate change conditions as expected in 2050.

7 Conclusions and recommendations

It is very likely that the climate will change in the Nzoia river catchment and increases in precipitation and temperature are consistently predicted by a suite of global circulation models. Remarkably climate change will provide important opportunities for both rain fed and irrigated agriculture in the downstream Bunyala plains as water availability will increase significantly. However, the analysis also showed that a complete shift to rain fed agriculture is not feasible.

A recent study from IFPRI (International Food Policy Research Institute, 2009) revealed that on a global scale agricultural productivity investments of around US$ 7 billion are required to overcome the negative impact of climate change on food production. Based on the results of the combined AquaCrop and WEAP analysis it is clear that the Bunyala irrigation scheme is a favourable place to invest in agricultural production: water is abundantly available now and in the future, and farmers interest and expertise is available. Besides the required investment in irrigation infrastructure a limiting factor might be distance to markets.

Flooding is however the major threat to these developments. Security levels of the embankments protecting the Bunyala plains are already relatively low and floods occur regularly. The already planned extension of the agricultural systems and the projected increase in extreme discharges and population growth increase the vulnerability of the Bunyala plains significantly. An important component of irrigation extension plans should be on a thorough flood risk assessment and an increase of security levels of the embankments to higher standards.

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