The potential of the System of Rice Intensification technique (SRI) in saving irrigation water and its impact on rice yield within Wami Basin in Tanzania: Application of the QSWAT model.

MSc. Thesis Report (45 ECTS)

By

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Master Degree Programme in Agro-Environmental Management.

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15th June 2017

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Preface

This thesis report is submitted to the Department of Agroecology, Faculty of Science and Technology, Aarhus University as partial fulfilment of the requirement for the award of Master of Science degree in Agro-Environmental Management.

The thesis involved a study of the potential of System of Rice Intensification (SRI) to save irrigation water and its impact on rice yield. The study was conducted in the Wami basin as a case study using a modelling software called QSWAT. Three scenarios of rice cultivation i.e. Control (no irrigation), Conventional rice cultivation (flooding method) and SRI were designed and simulated. Part of the study involved a 2-month field work in Tanzania, mainly for data collection but also for mentoring by the co-supervisor and his team at Sokoine University of Agriculture. The Project’s physical location in Aarhus University was at the Department of Bioscience, in Silkeborg. The project duration lasted from 1st September 2016 – 15th June 2017.
# Table of Contents

List of figures .................................................................................................................. vi

List of Tables .................................................................................................................. vii

Acronyms and Abbreviation ............................................................................................. ix

Abstract ............................................................................................................................ x

Summary ............................................................................................................................. xi

Acknowledgements ............................................................................................................ xiv

1.0 Introduction ................................................................................................................... 1

  1.1 Background ................................................................................................................... 1

    1.1.1 Overview of rice demand and production at global level .................................... 1

    1.1.2 Overview of rice demand and production in Tanzania ....................................... 1

1.2 An overview of river basins in Tanzania .................................................................... 1

1.3 The challenge in the Wami basin .............................................................................. 2

1.4 Way forward ................................................................................................................... 3

1.5 Research objectives .................................................................................................... 4

1.6 Research questions ..................................................................................................... 4

2.0 Theoretical framework ............................................................................................... 5

  2.1 Rice cultivation methods and their water use efficiency ......................................... 5

    2.1.1 Traditional flooding method (conventional rice cultivation) ........................... 5

    2.1.2 Integrated crop management (ICM) method ....................................................... 5

    2.1.3 Aerobic rice method ......................................................................................... 5

    2.1.4 System of Rice Intensification (SRI) ................................................................. 6

2.2 Water balance in a rice field ....................................................................................... 8

2.3 What is SWAT, ArcSWAT and QSWAT? ................................................................ 10

2.4 Examples of SWAT applications ............................................................................. 11

    2.4.1 SWAT in China .................................................................................................. 12
2.4.2 SWAT in Tanzania ........................................................................................................... 12
2.4.3 SWAT in South Korea ....................................................................................................... 13

3.0 Materials and methods ........................................................................................................ 15

3.1 Description of case study area .......................................................................................... 15
3.1.1 Location ......................................................................................................................... 15
3.1.2 Topography ..................................................................................................................... 16
3.1.3 Land use/land cover ....................................................................................................... 17
3.1.4 Soil .................................................................................................................................. 18
3.1.5 Sub basins ....................................................................................................................... 19
3.1.6 Climate ............................................................................................................................ 19
3.1.7 Socio-economic activities .............................................................................................. 20

3.2 Data requirement ................................................................................................................. 21
3.2.1 Model set up ................................................................................................................... 21
3.2.2 Model calibration and validation .................................................................................... 21
3.2.3 Scenarios design .............................................................................................................. 21

3.3 Data preprocessing .............................................................................................................. 23
3.3.1 DEM ............................................................................................................................... 23
3.3.2 Land use land cover map ............................................................................................... 23
3.3.3 Soil map .......................................................................................................................... 25
3.3.4 Weather data .................................................................................................................. 25
3.3.5 River flow data .............................................................................................................. 27
3.3.6 Visual exploration of rainfall and flow data ................................................................... 28

3.4 Model set up ....................................................................................................................... 31
3.4.1 Watershed delineation .................................................................................................... 31
3.4.2 HRUs creation ................................................................................................................ 31
3.4.3 Editing inputs, QSWAT set up and run .......................................................................... 32
5.2.2 Response of water balance components to irrigation scenarios ............................................ 62

5.2.3 Meaning and implications of the simulation results ................................................................. 63

6.0 Conclusions and perspectives ...................................................................................................... 64

6.1 Conclusions ................................................................................................................................. 64

6.2 Perspectives ................................................................................................................................. 64

7.0 References ..................................................................................................................................... 66

List of figures

Figure 1: A conceptual diagram showing water balance in a ponded rice field ......................... 9

Figure 2: A map showing three major sub catchments and location of the study area within the
Wami basin in Morogoro, Tanzania ................................................................................................. 15

Figure 3: Topography of the study area .......................................................................................... 16

Figure 4: LULC map of the study area ............................................................................................ 17

Figure 5: Distribution of soil types and texture in the study area .................................................. 18

Figure 6: The number and distribution of sub basins in the study area ........................................ 19

Figure 7: Total annual rainfall at SUA and Wami Prison station for 2007-2016 period .............. 29

Figure 8: Observed daily flow hydrograph at Mandera station (study site watershed outlet) for 2008-
2015 .................................................................................................................................................. 29

Figure 9: Observed daily flow hydrograph at Mandera station (study site watershed outlet) for 2008-
2015 .................................................................................................................................................. 29

Figure 10: A comparison of average monthly flow data a Mandera and Dakawa (assumed to be an
upstream point source) gauging stations ......................................................................................... 30

Figure 11: A screenshot of a SWAT Editor showing a portion of baseline management operation
file and sub basin number, soil type and slope in which the management operations were defined. 39

Figure 12: A section of the Wami River near UWAWAKUDA rice farms showing irrigation intake
canal and water level in the River as observed during field visit on February 16, 2017 ............... 42
Figure 13: Water intake for Mkindo irrigation scheme as observed during field visit on February 8, 2017. Weirs are encircled in red. ........................................................................................................45

Figure 14: Unpaved portion of main irrigation canal at UWAWAKUDA rice farms as observed during field visit on February 16, 2017.........................................................................................................................................46

Figure 15: Paved portion of main irrigation canal at UWAWAKUDA rice farms as observed during field visit on February 16, 2017 ........................................................................................................................................47

List of Tables

Table 1: A summary of comparison between conventional rice cultivation (CRC) method, system of rice intensification (SRI) and other methods .................................................................................................................6

Table 2: Data sets/information used in completion of this study and importance of each data/information ........................................................................................................................................................................21

Table 3: Land use look-up table and description of each land use, as used in this study showing land use ID in LULC map with a corresponding SWAT land use code ................................................................................25

Table 4: Missing rainfall data (%) SUA station for 2007-2016 period ..................................................................................................................26

Table 5: Missing rainfall data (%) at Wami Prison station for 2007-2016 period ...............................................................................................26

Table 6: Percentage of missing observed flow data at the watershed outlet (Mandera station) for three periods used in the model .................................................................................................................28

Table 7: Methodology applied in filling in data gaps in the point source data .................................................................................................32

Table 8: Selected parameters, method of change and initial maximum and minimum uncertainty ranges ........................................................................................................................................................................35

Table 9: Year 1 operations for CRC and SRI scenarios at Dakawa rice farms during wet season (the exact dates may vary) ........................................................................................................................................40

Table 10: Management operations for CRC, SRI and Control scenarios during dry season simulated for UWAWAKUDA rice farms (the dates are tentative except for the season) ........................43
Table 11: Final model parameter value ranges and fitted values (based on the best simulation) within 95 PPU........................................................................................................................................48

Table 12: Results of selected statistical criteria for evaluating the performance of model calibration and validation........................................................................................................................................50

Table 13: Irrigation amount and different stresses affecting rice yield for each of the simulated scenarios the specific HRU........................................................................................................................................56
### Acronyms and Abbreviation

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFSR</td>
<td>Climate Forecast System Reanalysis</td>
</tr>
<tr>
<td>CRC</td>
<td>Conventional Rice Cultivation</td>
</tr>
<tr>
<td>DED</td>
<td>District Executive Director</td>
</tr>
<tr>
<td>DFC</td>
<td>Danida Fellowship Centre</td>
</tr>
<tr>
<td>FAO</td>
<td>Food and Agriculture Organization of the United Nations</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>GLOWS-FIU</td>
<td>Global Water for Sustainability-Florida International University</td>
</tr>
<tr>
<td>HRUs</td>
<td>Hydrologic Response Units</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>QGIS</td>
<td>Quantum Geographic Information System</td>
</tr>
<tr>
<td>QSWAT</td>
<td>Quantum Soil and Water Assessment Tool</td>
</tr>
<tr>
<td>SRI</td>
<td>System of Rice Intensification</td>
</tr>
<tr>
<td>SUA</td>
<td>Sokoine University of Agriculture</td>
</tr>
<tr>
<td>SWAT</td>
<td>Soil and Water Assessment Tool</td>
</tr>
<tr>
<td>SWAT-CUP</td>
<td>Soil and Water Assessment Tool-Calibration and Uncertainty Programs</td>
</tr>
<tr>
<td>TMA</td>
<td>Tanzania Meteorological Agency</td>
</tr>
<tr>
<td>URT</td>
<td>United Republic of Tanzania</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>UWAWAKU</td>
<td>Kiswahili acronym for cooperative union for rice farmers using Dakawa DA</td>
</tr>
<tr>
<td>DA</td>
<td>irrigation scheme</td>
</tr>
<tr>
<td>WRBWO</td>
<td>Wami/Ruvu Basin Water Office</td>
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</tbody>
</table>
Abstract

The main objective of this study was to evaluate the water-saving potential of SRI technique and its impact on rice yield within Wami basin in Tanzania by using the QSWAT model. The model was set up, calibrated and validated using observed daily flow data for Wami river from WRBWO. Daily weather data from two stations near the study area, obtained from TMA, was used to represent the climate of the study area in the model. Model calibration and validation was done at a daily time step for 2012-2013 and 2014-2015, respectively using SWAT-CUP. Model performance was evaluated against thresholds recommended by Moriasi et al. (2015). The model performance can be considered satisfactory if $R^2 > 0.60$, $NSE > 0.50$ and $PBIAS \leq \pm 15 \%$, for watershed-scale models. The following performance was achieved for model calibration: $R^2 = 0.77$, $NSE = 0.76$ and $PBIAS = -13.7 \%$, whereas the validation achieved: $R^2 = 0.51$, $NSE = 0.50$ and $PBIAS = 3.8 \%$. Model prediction uncertainty had a $p$-factor $= 0.93$ and $r$-factor $= 1.49$ for calibration and $p$-factor $= 0.45$ and $r$-factor $= 1.27$ for validation. The model performance was considered satisfactory and used for scenario simulations. The results of scenarios show that up to 44% saving in irrigation water can be achieved by adopting the SRI in the study area without significant reduction in rice yield. This model can be considered an advancement from that of Wambura et al (2015) in describing the hydrology of the study area.
Summary

Over 50% of the world’s population depends on rice as their primary source of energy while the demand for rice keeps growing (Khush, 2005). Latest statistics by FAO (2017b) show that global paddy production has grown from around 690 million tons in 2008 to over 750 million tons in 2016. Global area under rice production has grown from around 160 million hectares in 2008 to around 165 million hectares as of 2017. Rice cultivation has some environmental consequence regarding water quantity and quality including use of large amounts of scarce water for irrigation as well as increased risk of water pollution e.g. by nutrients as pointed out by Zhi (1996). In Tanzania, rice is the second most cultivated cereal as food crop in Tanzania following maize (Kahimba et al., 2014). Area under rice production has grown from around 0.4 million ha in 2000 to about 1 million ha in 2014 with subsequent increase in total rice production from about 0.8 million tons in 2000 to over 2.6 million tons in 2014 (FAO, 2017a).

There are nine larger river basins in Tanzania (URT, 2014) and Wami basin is one of the areas where rice is grown (personal observation). The basin is faced by environmental degradation due to agricultural expansion, population growth and competition for water for diverse uses (Madulu, 2005). Consequently, a decline in the river flow during dry seasons has been observed, partly as result of declining rainfall and growing demand for water in the basin (Kiwango et al., 2015). This situation may be exacerbated by climate change in the basin as projected by (GLOWS-FIU, 2014) (pp. 63) consistent with the projected changes in the climate system for 2081-2100 relative to 1986-2005 by IPCC (2014). Given growing demand for rice in Tanzania while water is becoming a scarce resource, intensification of rice production using as little irrigation water as possible can be a way forward. Since SRI has shown great water saving potential (Kahimba et al., 2014; Reddy et al., 2005; Zhao et al., 2009), it could be a sustainable intensification solution.

This study therefore had the following specific objectives: Setting up, calibration and validation of QSWAT model for describing the hydrology of the case study area within the Wami basin; running scenario simulations for the conventional rice cultivation (CRC) method, the System of Rice Intensification (SRI) method and Control scenario (no irrigation) and assess potential impacts of the SRI on rice yield, downstream water users, river flow and sustainability of rice production in the Wami basin.

The study was conducted in one of the three sub catchments of the Wami basin between two main river gauging stations i.e. Dakawa and Mandera. As a first step, input data for the QSWAT model
was collected and preprocessed. Main types of data included open-source data i.e. Digital Elevation Model (DEM), land use/land cover satellite image data and soil map; and observation data from local authorities i.e. daily weather data and river flow data. Input data preparation was done using mainly QGIS 2.6.1 and Microsoft Excel. After input preprocessing, the model was set up by delineating the watershed, creating watershed and creating HRUs. The model set up was then followed by model calibration and validation. Calibration and validation was done using SWAT-CUP 2012. Sequential Uncertainty Fitting version 2 (SUFI 2) procedure was used in SWAT-CUP for validation and calibration. The validation was done for 2012-2013 period while calibrations was done for 2014-2015 period, both at daily time step.

A meta-analysis by Moriasi et al. (2015) showed that coefficient of determination ($R^2$), Nash-Sutcliffe efficiency (NSE) and percent bias (PBIAS) are the most widely reported model evaluation criteria. For this reason, NSE was used as an objective function in this study to calibrate and validate the model due to sufficient availability of reported values for ease of comparison of this study to other studies.

After calibration and validation, SWAT files with calibrated parameters were copied from SWAT-CUP project directory and used to replace their uncalibrated versions in the QSWAT project directory. The calibrated QSWAT model was then used to simulated three scenarios i.e. no irrigation (control scenario), CRC and SRI for both wet season (March-June) and dry season (August-November). The scenarios were designed such that the only variable between the scenarios was the amount of irrigation water in millimeters as done by Jung et al., (2014).

Results of model performance were evaluated based on recommended thresholds for stream flow by Moriasi et al. (2015). As per recommended thresholds, the model performance can be considered satisfactory if $R^2 > 0.60$, NSE > 0.50 and PBIAS $\leq \pm 15\%$, for watershed-scale models. The following performance was achieved for model calibration: $R^2 = 0.77$, NSE = 0.76 and PBIAS = - 13.7%. Model prediction uncertainty had a p-factor = 0.93 and r-factor = 1.49 for calibration and p-factor = 0.45 and r-factor = 1.27 for validation. This model was considered satisfactory for scenario simulations. Scenario analysis results showed that about 44% of irrigation water can be saved without significant reduction in rice yield. There was no significant difference in rice yield between CRC and SRI within a season but a difference of up to 20% in rice yield between wet and dry season noted; indicating that water is a limiting factor for rice growth during dry season in the study area.
Based on the results of this study, it can be concluded that the calibrated model can satisfactorily simulate river flow in the Wami basin, and perhaps the best model so far, that describes well the hydrology of the Wami basin. Thus, it can be concluded model results that up to 44% of irrigation water can be saved by adopting SRI without any significant impact in rice yield in the Wami basin.
Acknowledgements

Firstly, I would like to extend my sincere gratitude to my main supervisor, Jørgen E. Olesen, for accepting to supervise me on a very short notice and for all his constructive and valuable support and inputs during the entire duration of this thesis project.

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1.0 Introduction

1.1 Background

1.1.1 Overview of rice demand and production at global level

Over 50% of the world’s population depends on rice as their primary source of energy while the demand for rice keeps growing (Khush, 2005). It is estimated that rice production should be increased by about 40% to meet the growing demand by 2030 due to population growth and changing food habits (Khush, 2005). Latest statistics by FAO (2017b) show that global paddy production has grown from around 690 million tons in 2008 to over 750 million tons in 2016. Meanwhile, the world rice utilization is forecast to expand by 6.6 million tons in 2017/2018 and the global area under rice production has grown from around 160 million hectares in 2008 to around 165 million hectares as of 2017 (FAO, 2017b).

Rice has some environmental consequence regarding water quantity and quality. For example, a study by Zhi (1996) in China points out that traditional rice cultivation method (flooding) uses large amounts of irrigation water. Moreover, rice cultivation under flooded conditions has been associated with increased risk of water pollution because the excessive water carries nutrients e.g. nitrogen, fertilizer through seepage and percolation (Zhi, 1996).

1.1.2 Overview of rice demand and production in Tanzania

Rice is the second most cultivated cereal as food crop in Tanzania following maize (Kahimba et al., 2014). Area under rice production has grown from around 0.9 million ha in 2008 to about 1 million ha in 2014 with subsequent increase in total rice/paddy production from about 1.4 million tons in 2008 to over 2.6 million tons in 2014 (FAO, 2017a). Kahimba et al. (2014) point out population growth, growing urbanization and changing food habits as reasons for growing rice demand.

There is thus a challenge for us to meet the growing rice demand by pursuing more rice output from fewer resources namely limited land, less water, less chemicals, etc. (Khush, 2005). As pointed out by Pretty et al. (2011), agriculture of which rice cultivation is part, has to be intensified in the limited agricultural lands in order to avoid ecological damage which could be caused by farmers expanding production into forests and other ecologically sensitive lands (Khush, 2005).

1.2 An overview of river basins in Tanzania

There are nine larger river basins in Tanzania. The river basins are named as Internal Drainage Basin, Lake Nyasa Basin, Lake Rukwa Basin, Lake Tanganyika Basin, Lake Victoria Basin, Pangani Basin,
Rufiji Bain, Ruvuma and Southern Rivers Basin and Wami/Ruvu Basin. The Wami/Ruvu basin is in the eastern part of Tanzania and comprises of Wami river (a catchment area of about 43,742 km²) and Ruvu river (a catchment area of about 17,789 km²) as major rivers in the basin (URT, 2014). For clarity purpose, the catchment draining the Wami river will be referred to as Wami basin throughout this study since the catchment draining the Ruvu river is out of scope of this study.

1.3 The challenge in the Wami basin

A study by Madulu (2005) identified agricultural expansion as one of the environmental degradation problems in the Wami basin. The study also pointed out that there is rapid population growth and competition for water in the Wami basin for diverse uses. The uses include water for: industrial use (e.g. by sugar factory), livestock keeping, large and small-scale irrigation agriculture (e.g. sugar plantation), large domestic water supply project for Chalinze township and surrounding villages, wildlife (Saadani National Park and Wami-Mbiki wildlife management area), etc. Agriculture in the basin is predominantly small scale despite the large-scale sugar plantation. Rice (paddy) is among the main crops grown in the Wami basin apart from sugar cane, maize, sweet potatoes, cassava, vegetables, fruits, coconut and legumes (Madulu, 2005). A recent study by Kiwango et al. (2015) on the recommended minimum river flow in the river shows that fresh water flow to the Wami River estuary is declining due to declining rainfall but also due to growing water demand in the Wami river basin for large and small scale agriculture (including irrigation schemes). The study also reports to have commonly observed a minimum flow during a dry season which was 30 % less than the recommended minimum river flow. Changes in land and water resources use are thought to be the main causes for observed decline in river flow in the Wami River, and partly due to declining rainfall (Kiwango et al., 2015). In addition, (GLOWS-FIU, 2014) (pp. 63) point out that climate projections for the area around the Wami basin for the 21st century show trends of increasing temperatures, evapotranspiration and soil moisture deficits and frequency of extreme events such as high rainfall, floods and droughts. This projection is consistent with the projected changes in the climate system for 2081-2100 relative to 1986-2005 by IPCC (2014).

Given the growing demand for rice, population growth and potential ecological consequences of agricultural expansion, intensification could be the way forward as pointed out earlier. According to Pretty et al. (2011), traditionally, agricultural intensification can be defined as (i) increasing yields per hectare, (ii) increasing the number of crops or amount of inputs e.g. water per unit of land (iii) changing land use from low value crops or commodities to those of high value.
One way of increasing yield per unit of land is by using better rice varieties with not only high yield potential but also stable yield (Khush, 2005). On the other hand, change in the cultivation and management practice can achieve high yields per unit of land, as in the case of the System of Rice Intensification (SRI). It can be inferred from Stoop et al. (2009) that SRI is a concept based on manipulation of agronomic principles to attain higher rice yields with minimal inputs i.e. water, seeds and agrochemicals. Several studies have shown that SRI can achieve high yields with less inputs. According to Reddy et al. (2005), one of the distinguishing features of SRI is its use of less resources such as seeds, water (no continuous flooding in SRI compared to traditional method) and agrochemicals. Results of field experiments by Zhao et al. (2009) in China demonstrated that SRI can achieve higher yields with less irrigation water (high water use efficiency) compared to traditional flooding method also called conventional rice cultivation (CRC) method. SRI also showed higher nitrogen use efficiency as higher grain yield was attained at significantly lower nitrogen rate compared to traditional flooding method (Zhao et al., 2009).

Similar experiment conducted in Tanzania in an area within the Wami basin (Mkindo area in Morogoro region), for two consecutive years on experimental plots and farmers’ fields, by Kahimba et al. (2014), on the rice water productivity of SRI revealed promising results. The grain yield of up to 6.3 tons/ha was obtained under SRI compared to 3.8 tons/ha under traditional flooding method. On water use and water productivity, the traditional flooding method had a mean irrigation water use of 2.8 m$^3$/m$^2$ while SRI had around 1 m$^3$/m$^2$, equivalent to over 60 % water saving through reduction of irrigation water.

1.4 Way forward

From the above literature review, the following conclusion can be drawn: the demand for rice is growing in Tanzania while water is becoming a scarce resource, hence rice production should be intensified instead of expansion to minimize potential environmental consequences. It is therefore clear that rice demand should be met by using as little irrigation water as possible. Since SRI has shown great water saving potential, it could be a sustainable intensification solution. However, little information was available in literature to quantitatively demonstrate the potential irrigation water saving that could be achieved, at a watershed scale, by adopting SRI in the Wami basin, Tanzania. This thesis study sought to fill this research gap by simulating and comparing three rice cultivation scenarios (Control, conventional flooding method and SRI) and evaluate their impact on rice yield, river flow, downstream water users and sustainability of rice cultivation in the Wami basin.
The term sustainability in the context of this study implies that the rice cultivation method neither decreases rice yield significantly nor does it impair water availability for ecosystem functioning or other human activities. The assessment was done by applying the Quantum Soil and Water Assessment Tool (QSWAT) to the case study area.

1.5 Research objectives

The main objective of this thesis work was to evaluate the water-saving potential of SRI technique and its impact on rice yield within the Wami basin by using the QSWAT model. This main objective was attained by breaking it down into the following specific objectives:

i. Setting up, calibration and validation of QSWAT model for the case study area within the Wami basin.

ii. Running scenario simulations for the conventional rice cultivation (CRC) method, the System of Rice Intensification (SRI) method and Control scenario (no irrigation).

iii. Assess potential impacts of the SRI on rice yield, downstream water users, river flow and sustainability of rice production in the Wami basin.

1.6 Research questions

The specific objectives were attained by answering the following research questions:

i. Can QSWAT satisfactorily simulate natural stream flow for the study area within the Wami basin?

ii. How does the rice yield differ between the CRC and SRI scenarios?

iii. What could be potential impacts of the SRI method on rice yield, downstream water users, river flow and sustainability of rice production in the Wami basin?
2.0 Theoretical framework

2.1 Rice cultivation methods and their water use efficiency

The purpose of this section was to gain an insight from the literature about different types of rice cultivation methods and their main differences. This was useful in the formulation of research objectives, questions, and general execution of the study, including the design of agricultural management scenarios simulated using the QSWAT model. According to a review by Stoop et al. (2009) four rice cultivation methods could be identified based on agronomic practices underlying these methods. The methods are traditional flooding method, integrated crop management (ICM) method, the system of rice intensification (SRI) method and aerobic rice method (also known as upland rice). The focus of Stoop et al. (2009) was on the weaknesses of studies comparing different rice production systems, yet the study provided a starting point for identifying types of rice production systems and their main characteristics.

2.1.1 Traditional flooding method (conventional rice cultivation)

This method is characterized by the following recommended cultivation practices: transplanting of seedlings that are about 25 days old, transplanting of 3-4 seedlings per hill, planting in rows (0.15 x 0.1m spacing), hand weeding and continuous flooding (Balasubramanian et al., 2005).

2.1.2 Integrated crop management (ICM) method

There is no ubiquitous definition of ICM but it can simply be referred to as a combined use of appropriate techniques in crop production that meet the need of farmers thus improving productivity and income. ICM is characterized by the following practices: transplanting of seedlings that are 15-20 days old (growth stage with 4 leaves), transplanting 1-2 seedlings per hill, square planting (0.2 x 0.2m to 0.25 x 0.25m spacing), mechanical weeding and soil stirring using rotating hoe; and intermittent irrigation. The method also employs the use of integrated pest management techniques (including herbicides)(Balasubramanian et al., 2005).

2.1.3 Aerobic rice method

Essentially, aerobic rice (also called upland rice) cultivation method involves growing the rice like an upland irrigated crop as in the case of maize or wheat. Unlike the traditional flooding method, aerobic rice is grown in non-saturated soil with no ponded water; the method is aimed at dealing with ever increasing water scarcity (Bouman et al., 2005). However, Bouman et al. (2005) point out that research has shown that achieving high yields under aerobic method requires a selection of rice
varieties that combine traits of high yielding lowland variety and upland drought resistant variety. As per experiment by Bouman et al. (2005), the aerobic rice method can be characterized by the following: use of improved upland variety, transplanting of seedlings at age of 21 days, transplanting of 3 seedlings per hill, planting in rows at 0.25 x 0.1 m spacing and maintaining moist but aerobic soils instead of saturated (flooded) soils. The method also uses mineral fertilizers to boost yields as well as herbicides and manual weed control in pest management.

2.1.4 System of Rice Intensification (SRI)

According to Stoop et al. (2009), the SRI was invented in Madagascar and first reported by de Laulanie´, a Jesuit priest, in 1993. Six main agronomic principles characterize this rice cultivation method: transplanting of seedlings that are around 10 days old; transplanting of 1 seedling per hill, wide spacing of transplants (0.25 x 0.25 m to 0.5 x 0.5 m), alternate wetting and drying of soil, regular weeding and soil aeration by using rotary hoe and use of organic fertilizers. Table 1 summarizes some main agronomic practices that characterize the different rice cultivation methods as per review by Stoop et al. (2009).

Table 1: A summary of comparison between conventional rice cultivation (CRC) method, system of rice intensification (SRI) and other methods

<table>
<thead>
<tr>
<th>Rice cultivation method</th>
<th>Seed requirement (kg/ha)</th>
<th>Age of seedlings (days)</th>
<th>Number transplants /hill</th>
<th>Spacing of hills (cm)</th>
<th>Number of transplant s/m²</th>
<th>Water management</th>
<th>Fertilizer management</th>
<th>Weed management</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRC</td>
<td>80-120</td>
<td>20-30</td>
<td>3-4</td>
<td>Normally in rows of 10 x 10 to 20 x 20</td>
<td>75-150</td>
<td>Continuous flooding</td>
<td>Basal mineral fertilizer and nitrogen top dressing</td>
<td>2 rounds with a rotary hoe but herbicide use is prevalent</td>
</tr>
<tr>
<td>Method</td>
<td>ICM</td>
<td>Aerobic</td>
<td>SRI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>anny</td>
<td>10-30</td>
<td>20-120</td>
<td>5-10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15-21</td>
<td>21</td>
<td>8-12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-2</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20 x 20 to 25 x 25</td>
<td>25 x 10</td>
<td>25 x 25 to 50 x 50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16-50</td>
<td>120</td>
<td>4-16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>intermittent irrigation, soil is saturated to 5 cm flooding</td>
<td>soil is kept moist through intermittent wetting and drying</td>
<td>soil is kept moist via intermittent wetting and drying</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Organic and mineral fertilizer</td>
<td>Basal mineral fertilizer and nitrogen top dressing</td>
<td>Mostly organic fertilizer but mineral fertilizer can also be used as supplement when needed and available</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mechanical and manual weeding, herbicides are also used</td>
<td>Mechanical or manual and herbicide</td>
<td>3-4 rounds using a rotary hoe</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Adapted from Stoop et al. (2009)
Results of an experimental study conducted by Bouman et al. (2005) in the Philippines showed that a total water input of 1240-1880 mm was used (for land preparation and crop growth) under flooded rice cultivation while a total of 790-1430 mm was used under aerobic method. It was also interesting to note that aerobic rice fields used less water in land preparation, seepage and percolation, evaporation and transpiration than flooded rice fields. However, it was found that on average, mean yield of all varieties was 32 % lower for aerobic conditions than in flooded conditions during dry season and 22 % lower for aerobic method than for flooded method during wet season. The maximum yield attained under aerobic condition ranged from 5.7 to 6 t ha\(^{-1}\).

On-station experiments by Balasubramanian et al. (2005) in India revealed that full ICM practices could result in grain yields of up to 7.1 t ha\(^{-1}\) compared to 5.8 t ha\(^{-1}\) under full CRC practices. The study also reports an on-farm evaluation of ICM in which a 25 -30 % savings in irrigation water was achieved.

For SRI, Jagannath et al. (2013) conducted a meta-analysis on 29 published studies to assess the differences between SRI and non-SRI rice cultivation practices in terms of total and irrigation water use. Total water use referred to a summation of irrigation water and rainfall during crop growth. It was found that an average total irrigation water use for experiments with SRI method was around 1200 mm compared to around 1500 mm under conditions which employed non-SRI rice cultivation methods, equivalent to 22 % irrigation water saving. Jagannath et al. (2013) point out that 17 studies specifically reported and analyzed irrigation water use. Here it was found that an average irrigation water use was 720 mm under SRI methods compared to 1100 mm under non-SRI methods, equivalent to 35 % irrigation water saving. Paddy yield for SRI trials averaged 5.9 tons ha\(^{-1}\) compared to 5.3 tons ha\(^{-1}\) under non-SRI trials.

2.2 Water balance in a rice field

The purpose of this section was to gain an insight from literature on what happens to water balance in a typical rice field. Understanding what happens to water balance at the field level is important because as Arnold et al. (2009, pp. 8) and Arnold et al. (2012) point out the water balance is the primary driver of everything that happens in a watershed for any problem studied by using SWAT model. In a flooded rice field, the water balance dynamics includes storage, gain and losses as illustrated in Figure 1 from Sivapalan (2015). The figure shows that if we consider a soil surface of a flooded rice field, water gains include rainfall and irrigation, whereas water losses include transpiration, evaporation and infiltration. Runoff and seepage contribute the flow of water both into-
and out of the rice fields. In Figure 1, seepage implies movement of water through rice field bunds; infiltration implies vertical movement of water into the soil from the soil surface whereas deep percolation implies downward drainage of water out of root zone to ground water.

**Figure 1**: A conceptual diagram showing water balance in a ponded rice field

Source: Adapted from Sivapalan (2015)

According to Sivapalan (2015) water losses in a ponded rice field can be categorized into two main groups namely gaseous phase losses and liquid phase losses. Gaseous phase losses include water lost in form of vapor during transpiration by a plant and during evaporation from water surface. Liquid phase losses occur when water percolates down through the soil due to gravitational pull and through runoff of excess water over field bunds. An experiment by Sivapalan (2015) shows that both evaporation and transpiration (evapotranspiration) are driven by solar energy. However, amount of transpiration also depends on the leaf area. It was found that amount of water lost via evaporation was higher (up to 7 mm/day) during initial stages of rice growth compared to that lost (up to 4 mm/day) when the rice was close to full canopy. As the rice approached maturity, the evaporative losses
decreased due to shading effect provided by now larger rice canopy on water surface. However, the transpiration losses were almost double (8.6 mm/day) the evaporative losses (4.4 mm/day) at full canopy because of larger leaf surface area at this growth stage.

It is explained by Sivapalan (2015) that percolation is the downward movement of water through a saturated soil column. This movement, is driven by gravitational pull and hydrostatic pressure exerted by the ponded water column (for the case of flooded rice field). The amount of water lost through percolation depends on the soil texture and the depth of water column from the soil surface, heavy clay soils have less percolation losses while less clayey soils have more percolation losses (Sivapalan, 2015).

2.3 What is SWAT, ArcSWAT and QSWAT?

The purpose of this section is to provide a brief description of the concepts of the SWAT model including examples of equations that are used in the model. The section also intends to provide an insight into interfaces used by the SWAT model. The Soil and Water Assessment Tool (SWAT) is an eco-hydrological model developed for simulating the impacts of management (e.g. agricultural management practices) on water, nutrient, pesticides and sediment yields in watersheds/river basins. The model operates in a daily time step and is composed of several components that represent physical processes taking place in a river basin. SWAT was first developed in the early 1990s and it has since then undergone a lot of improvements including multiple hydrologic response units capability (Arnold et al., 2009). SWAT can partition a watershed into smaller sub basins that each will contain a segment of a river (the user can define the size of these sub basins, and depends on the purpose of the study and the level of data available). Each sub basin is further subdivided into hydrologic response units (HRUs), which represent a unique combination of landcover, soil type and landscape slope. The HRUs are the key building blocks and computational units of SWAT (Arnold et al., 1998 and Arnold et al., 2012). For each HRU, the model has components that account for hydrology, agricultural management practices, pesticides, nutrients (Nitrogen and Phosphorus), sediments, soil temperature, crop growth and weather (Arnold et al., 1998, Arnold et al., 2012b).

Physically based models represent these components, thus in essence, the SWAT model is made up of a multitude of models that work together. For example, the hydrology component is represented by a hydrological model based on a water balance equation (1) from Arnold et al., (2009, pp. 9)

\[ SW_t = SW_o + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \]  

(1)
where $SW_t$ and $SW_o$ denote final and initial soil water content respectively on day $i$, $t$ denotes time in days, $R_{day}$ denotes the amount of precipitation on day $i$, $Q_{surf}$ is the quantity of surface runoff on day $i$, $E_a$ denotes the amount of evapotranspiration on day $i$, $W_{seep}$ denotes the quantity of water entering the vadose zone from the soil profile on day $i$ and $Q_{gw}$ is the quantity of return flow on day $i$, all units in millimeters of water (mm H$_2$O) except for $t$ which is in days (Arnold et al., 2009, pp. 9). This concept of the hydrology component in SWAT model was especially relevant because hydrology is the driving force in SWAT as explained by Arnold et al. (2009, pp. 8) and Arnold et al. (2012).

The SWAT model can simulate both dryland and irrigated agriculture. Irrigation application can be manual or automatic. Manual irrigation application will require a user to specify, application date, amount of irrigation, and efficiency of application whereas automatic application requires the user to specify efficiency of application and plant water stress level at which the irrigation will be automatically triggered.

This concept of irrigation water application is relevant for this study because irrigation water management is among the factors distinguishing the SRI from CRC method. Thus, by manipulating irrigation practices in SWAT, it was possible to answer the research questions of this study.

SWAT uses various GIS interfaces for example ArcGIS, hence the most common interface called ArcSWAT. The GIS interface is used for generation of input data for SWAT model. A new interface called QSWAT uses an open source GIS interface called QGIS where SWAT is installed as a plugin (Dile et al., 2016b). The QSWAT is essentially like the ArcSWAT except that the former is an open source software with additional capability of merging smaller sub basins and options for static and dynamic visualization of model outputs (Dile et al., 2016b). The QGIS interface and hence QSWAT was chosen for this study primarily because of having open source advantage over the other interfaces.

### 2.4 Examples of SWAT applications

This section intends to provide an insight into SWAT model applications to solve watershed/river basin-related problems around the world, including Tanzania. The section reviews examples of studies conducted in different parts of the world, highlights concepts relevant for the Master’s thesis project and points out the importance of those concepts. A review by Gassman et al. (2007) reveals that SWAT has been extensively applied in the US and Europe and the application has been expanding globally in recent decades. The authors point out that main SWAT applications found in literature are in the following categories: applications dealing with hydrological assessments, applications related
to climate change impacts, applications concerning calibration and/ or sensitivity analysis, applications describing GIS interface, applications studying variation in configuration or data input effects, applications comparing SWAT with other models, interface with other models and applications concerning pollutant assessments. An important concept from this review that was relevant for answering research questions for this study is the fact pointed out by Gassman et al. (2007) that, regardless of the focus of any SWAT application category, simulation of hydrologic balance is a foundation of any SWAT study.

2.4.1 SWAT in China

An interesting study illustrating a specific SWAT application includes a case study by Nielsen et al. (2013) where the focus was on assessing ways to combat eutrophication (a form of nutrient pollution) in a drinking water reservoir in China. The authors coupled SWAT model with an empirical equation for estimating total phosphorus (TP) concentrations in the reservoir; demonstrating the SWAT’s capability to work with other modelling tools. Although this study specifically focused on estimating TP load to the reservoir and subsequently estimating how much nutrient load reductions are required in attaining minimum drinking water quality standards, as well as assessing possible mitigation measures to achieve the estimated reductions, it was extremely relevant for this thesis project because it provided useful insight into main types of data requirement and their potential sources. Also, data set used by Nielsen et al. (2013), along with a tutorial on this data by Trolle (2016), were extremely useful learning tools and guide in setting up the QSWAT model for this thesis study.

2.4.2 SWAT in Tanzania

In Tanzania, Wambura et al. (2015) applied SWAT to assess the uncertainty of runoff projections under changing climate in the Wami basin. The focus of the study was to evaluate the uncertainty of future stream flow simulations using inputs from a range of climate projections from General Circulation Models (GCM), considering the increasing water demands (Wambura et al., 2015). The relevance of this study is that: firstly, the study provides a clear insight into types and sources of local data requirement in addition to the potential open data sources used by Nielsen et al. (2013). For example, it reveals that daily rainfall and temperature data for the Wami basin (1977-2010) was obtained from Tanzania Meteorological Agency (TMA) whereas daily stream flow data and water uses data in the basin was obtained from Wami/Ruvu Basin Water Office (WRBWO). Secondly, the study by Wambura et al. (2015) reveals that the basin has 3 major catchments namely Kinyasungwe, Mkondoa and Wami. Each catchment has a flow gauging station with Mkondoa at
Dakawa flow gauge, Kinyasungwe at Godegode flow gauge and Wami catchment at Mandera flow gauge. However, it is pointed out that the stream flow data used in calibration and validation was from the Mandera flow gauge (between 1977 and 2010 with 37% missing data) only because the data from the other two stations lacked reliable information for model calibration. Wambura et al. (2015) point out that they applied SWAT-Calibration and Uncertainty Program (SWAT-CUP) as a way of dealing with the missing data because of its capability to carry out calibration with missing records. Similarly, SWAT-CUP was applied in this thesis project.

2.4.3 SWAT in South Korea

Jung et al. (2014) conducted a modelling study which aimed at evaluating potential water saving, at a watershed scale, which can be realized from SRI compared to conventional rice cultivation practices in South Korea. The study also evaluated nutrient loading reductions which could be attained under SRI. This study is particularly interesting because it relates closely to what was done in this thesis work, hence it is presented in more detail here. The study used a program called SWAPP (SWAT-APEX) which is a program developed by the US Environmental Protection Agency (EPA) where APEX stands for Agricultural Policy/Environmental eXtender (Jung et al., 2014). This program is reported to be a combination of SWAT model and APEX model, of which it is described that APEX is a field scale model capable simulating detailed field conditions i.e. nutrient concentrations, runoff volume, carbon dynamics in soil-plant systems and nutrient loadings from specific management practices on a daily time step for several fields in each simulation. The APEX has a capability to simulate water balance and transport of nutrients for paddy at field scale whereas SWAT can do so at watershed scale. The two models were therefore combined for achieving higher efficiency and reliability water quality simulations by harnessing the strengths of each model simultaneously (Jung et al., 2014). However, SWAT can also simulate water balance and nutrient transport for paddy both at field and watershed scale by appropriately defining an HRU (Dennis Trolle, personal communication) at the relevant field scale level. In this thesis work, the Dakawa rice farms were defined as a unique HRU and used as a focus area for scenario simulations. The evaluation of the effects of SRI by (Jung et al., 2014) was only based on water management scenarios since there was not sufficient information available for all SRI management practices (Jung et al., 2014). Analysis of scenarios involved evaluation of ponding depths (irrigation depth) of 20, 40, 60, 80 mm and recommended depth by government for alternating wetting and drying (AWD) irrigation management. The results of the ponding depths were then compared with records of amount
of irrigation water withdrawn from reservoir. It was found that the 20 mm, 40 mm and recommended irrigation depth saved irrigation water by 68, 28 and 17% respectively (Jung et al., 2014). The concept of irrigation depth manipulation in SWAT was adopted in achieving the objectives of this thesis study.
3.0 Materials and methods

3.1 Description of case study area

3.1.1 Location

The case study area is located between two major river gauging stations i.e. Dakawa and Mandera (Fig. 2) in one of the three sub catchments of the Wami basin. The Wami basin, found between latitudes 5-7º S and longitudes 36-39º E (Wambura et al., 2015), comprises of three major sub catchments (Fig. 2) namely Kinyasungwe (located West of the basin), Mkondoa (located mid-south of the basin) and Wami (study area, located north-east of the basin) (GLOWS-FIU, 2014; pp.15; Wambura et al., 2015). Wami basin has an area of about 43, 000 km² (GLOWS-FIU, 2014)(pp.34) of which the study area covers around 10, 000 km² located between latitude 5.3-6.7º S and longitude 36.7-38.4º E (extents of DEM of study area).

Figure 2: A map showing three major sub catchments and location of the study area within the Wami basin in Morogoro, Tanzania
3.1.2 Topography

As per Atlas of water resources for Wami/Ruvu basin by GLOWS-FIU (2014) (pp.38), the study area spans an elevation of 100 m to more than 2100 m above sea level. The highest elevation (2400 m) is found on Nguru mountains (identifiable by elevation 1613-2382 m in Figure 3) within the study area.

Figure 3: Topography of the study area
3.1.3 Land use/land cover

The approximate distribution of major land use/land cover (LULC) in the study area after classification of a satellite (Landsat 7) image is as follows: Natural forest covers 122,077 ha (11 %), woodland covers 337,972 ha (31 %), bushland covers 493,768 ha (45 %), wetland covers 13,241 ha (1 %), general agricultural land covers 98,318 ha (9 %), sugar cane covers 13,173 (1 %) and rice covers 17,027 ha (2 %). Waterbodies and built up areas both cover less than 1 %. Figure 4 shows the LULC distribution in the study area.

Figure 4: LULC map of the study area
3.1.4 Soil

As per description of (FAO, 2003), the study area can loosely be described to have Ferric Acrisols, Chromic Cambisols, Orthic Ferrasols, Eutric Fluvisols and Pellic Vertisols soil types. Soil textures in the study area include both sandy, loamy and clayey type. The soil type and texture distribution in the study area is shown in Figure 5.

Figure 5: Distribution of soil types and texture in the study area
3.1.5 Sub basins

Watershed delineation process, as it will be seen later in section 3.4, resulted into a total of 88 sub basins for the study area (Fig. 6). Management scenarios were defined and simulated in a specific HRU in sub basin 52 (highlighted in yellow in Fig. 6). A point source whose discharge defines a boundary condition between the study area and the rest of the Wami basin is in sub basin 60. Irrigation water for scenarios, as it will be seen later in section 3.7, is drawn from sub basin 67 (approximate to the actual location of irrigation water intake for the UWAWAKUDA rice farms). Sub basin 88 is the watershed outlet representing the location of the historical flow data used in model calibration and validation.

![Image of sub basins]

Figure 6: The number and distribution of sub basins in the study area

3.1.6 Climate

Wami basin receives varied amounts of rainfall as it spans from the Indian ocean (Eastern Tanzania) through Eastern arc mountains (Nguu, Nguru and Rubeho) to a semi-arid central Tanzania. Wami/Ruvu Atlas by GLOWS-FIU (2014), shows that a large part of the study area receives average
annual rainfall between 800 mm and 1100. A small area especially around Nguru mountains (recognizable by elevation1613-2382 in Fig. 3 in section 3.1.2), receives between 1200-1300 whereas a smaller area (top of Nguru mountains) receives >1300 mm. The study area receives a bimodal rainfall i.e. between October and December and March and May (Wambura et al., 2015). Temperature analysis over 1901 to 2002 period shows that mean annual temperature in the study area ranges between 16°C and 25°C (GLOWS-FIU, 2014).

3.1.7 Socio-economic activities

A situation analysis report by IUCN (2010)(pp.25-40) highlights various social economic activities in the Wami basin with regard to how those activities impact water resources among other things. These activities include industries, agriculture, pastoralism, rural and urban water supply. There is only one large scale sugar factory in the Wami basin i.e. Mtibwa Sugar Company, located in Mtibwa village, Mvomero District.

Agricultural activities in the Wami basin include rainfed crop cultivation and irrigation schemes. Dakawa paddy irrigation scheme (belonging to UWAWAKUDA (Thomas P. Kakema, personal communication)) and Mtibwa sugar estate are two large irrigation schemes in the basin. There are also small and medium scale irrigation schemes in the basin.

Pastoralism is also highlighted as a major socio-economic activity in the Wami basin, especially in Kilosa and Mvomero districts due to availability of good pasture and relatively plentiful water.

Rural and urban water supply activities include ‘Wami Water Supply System’ which supplies water to 20 villages in Bagamoyo district, including Chalinze township at the time (Madulu, 2005; GLOWS-FIU, 2014) and ‘Dodoma Urban Water Supply and Sewerage Authority’ (DUWASA) which supplies water mostly to Dodoma municipality. Wami water supply system completely depends on Wami river whereas DUWASA depends on boreholes (located about 35 km outside Dodoma municipality; not shown on map) (GLOWS-FIU, 2014).

The two large irrigation schemes (Dakawa paddy irrigation and Mtibwa sugar estate) and the sugar factory fall within the case study area. On the other hand, the two large water supply schemes namely DUWASA and the Wami Water Supply System fall outside the case study area (although they are still located within the greater Wami basin).
3.2 Data requirement

3.2.1 Model set up

The model set up involved watershed delineation, watershed creation and HRU creation. This step required Digital Elevation Model (DEM) for watershed delineation, Land use/land cover (LULC) map for HRU creation and Soil map for HRU creation as used in many SWAT studies including Nielsen et al. (2013) and Wambura et al. (2015). The sources of the data are shown in Table 2.

3.2.2 Model calibration and validation

Model calibration and validation used observed daily river flow data, daily weather data (solar radiation, wind speed, relative humidity, rainfall and maximum and minimum temperature). The data sources are shown in Table 2.

3.2.3 Scenarios design

The design of scenarios relied on information on typical management operations for the Dakawa irrigation scheme and Mkindo irrigation scheme in the study area. The management operations included typical dates for planting and harvesting and depth of irrigation water used for CRC and SRI.

Another data requirement includes: irrigation water abstraction statistics in the study area for comparing the simulated irrigation water use with actual irrigation water use as done by (Jung et al., 2014). Observational data on rice yields was also important for assessing whether or not the outputs of model simulations are realistic as recommended by (Arnold et al., 2012b). The data sources are shown in Table 2.

Table 2: Data sets/information used in completion of this study and importance of each data/information

<table>
<thead>
<tr>
<th>Data</th>
<th>Use in the SWAT model</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEM; 30 m resolution</td>
<td>Watershed delineation</td>
<td>Shuttle Radar Topography Mission (SRTM) downloaded from <a href="http://earthexplorer.usgs.gov/">http://earthexplorer.usgs.gov/</a></td>
</tr>
<tr>
<td><strong>LULC satellite image (LANDSAT 7 ETM+)</strong></td>
<td>Lan use and land cover map for HRUs creation</td>
<td>USGS Global Visualization Viewer (GloVis) downloadable from <a href="http://glovis.usgs.gov/">http://glovis.usgs.gov/</a></td>
</tr>
<tr>
<td><strong>Soil map</strong></td>
<td>HRUs creation</td>
<td>FAO (2003)</td>
</tr>
<tr>
<td><strong>Observed weather data (daily rainfall, solar radiation, temperature, relative humidity, and wind speed) for period 1/1/2007-12/31/2016</strong></td>
<td>Drive the hydrological balance in the model</td>
<td>-A complete dataset from Morogoro station (about 40 km from the study area) was obtained from TMA -Also, rainfall records from one station at the boundary of study area was obtained from WRBWO</td>
</tr>
<tr>
<td><strong>Water flow records in the study area</strong></td>
<td>Used in calibration and validation</td>
<td>WRBWO</td>
</tr>
<tr>
<td><strong>Management operations for conventional rice cultivation and SRI; rice yields</strong></td>
<td>Used in scenario simulation and to ensure that model results in terms of rice yield are reasonable under base scenario</td>
<td>Obtained from interview with farmers during field visits to Mkindo irrigation scheme and Dakawa irrigation scheme on 8 Feb. 2017 and 16 Feb. 2017 respectively.</td>
</tr>
<tr>
<td><strong>Total size of rice farms in Dakawa and sugar plantation in Mtibwa (largest irrigation schemes in the study area)</strong></td>
<td>Used to aid accurate classification of satellite image to produce land cover land use map</td>
<td>Interview with chairman of rice farmers’ cooperative in Dakawa (UWAWAKUDA) and literature (for size of sugar plantation)</td>
</tr>
<tr>
<td><strong>Observed location of some streams in the study area</strong></td>
<td>Aided in watershed delineation</td>
<td>Obtained during field visit to D Mkindo (February 8, 2017) and Dakawa (February 16, 2017).</td>
</tr>
</tbody>
</table>
### 3.3 Data preprocessing

#### 3.3.1 DEM

The Shuttle Radar Topography Mission’s (SRTM) DEM of 30 m resolution for Wami River basin was downloaded from [http://earthexplorer.usgs.gov/](http://earthexplorer.usgs.gov/) and preprocessed according to the user guide manual by (George, 2015b). On downloading the DEM (in .tif file format), the coordinates of the Wami River basin (5-7° S and 36-39° E) were obtained from Wambura et al. (2015) and used as extent on download form. The actual latitudes used for downloading the DEM were -4.0 and -8.0° S whereas actual longitudes used were 34.0 and 40.0° E. After downloading, the grids were clipped by using the following coordinates (x, y) 34.0, -4.0 and 40.0, -8.0 where x is longitude and y is latitude. After clipping, the grids were merged, the resulting DEM was re-projected to Arc 1960/UTM Zone 37 S from the original WGS 84 projection. The re-projected DEM was then masked by using the Wami basin shapefile.

To reduce processing time owing to a large size (over 104 million cells) of the high-resolution DEM (30 m), a prior delineation was done using a coarser (90 m) DEM of the Wami basin and the extent of the sub basins that fell between Dakawa and Mandera gauging stations was used to clip the 30 m DEM. The size of the 30 m DEM was thus reduced from over 104 million cells to just over 42 million cells. The clipping was done using the following coordinates (x, y) (36.5994637524, -5.27684484175) and (38.5781612612, -6.84458209879).

#### 3.3.2 Land use land cover map

LULC satellite images (Landsat 7 Enhanced Thematic Mapper plus) for the study area were downloaded by using path 166-167 and row 64. The path and row for the study area were identified from NASA (2017). The satellite images (in .TIF format), dated June 2015, had 8 spectral bands whereby each band is contained in a single image. The latest images were desirable but the study area was cloudy most of the time, hence the images on June 2015 were the latest images found to have smallest cloud cover (cloud cover w 0 %). The following procedure was then used in pre-
processing the downloaded images: gap filling, merging, clipping, re-projecting, classification, editing and finally preparation of SWAT land use CSV file for use in QSWAT.

The gap filling was necessary because Landsat 7 images collected since 2003 have missing data due to sensor malfunction and therefore the downloaded images come with a gap-fill dataset (gap mask)(USGS, 2015). The gap mask was applied on each image representing each of the eight spectral bands (using ‘Raster>Analysis>fill no data’ tool in QGIS 2.6.1). Landsat 8 images were first considered since they do not have similar disadvantage of missing data as those of Landsat 7, however the latter was chosen because they appeared to have consistently smaller cloud cover compared to the former. The merged image was then clipped by using a shapefile of the study area as a mask, followed by re-projection to Arc 1960/UTM Zone 37 S from the original WGS 84 projection.

The clipped image (raster file) was then classified into natural forest, woodland, bushland, built up area, water, wetland and cultivated land by using semi-automatic classification plugin (SCP) in QGIS by (Congedo, 2017). The SCP allows a supervised classification of land cover types by different combinations of spectral bands. For example, band combination ‘RGB = 5-4-3’ makes vegetation more visible by appearing as red (an illustration can be found in page 145 of Congedo (2017)). There are different options for classification algorithms in the SCP but ‘spectral angle mapping’ was used in this study as it was pointed out by Congedo (2017) (page 154) to be the most commonly used. Most of the land cover type classification is adopted from National Forestry Resources Monitoring and Assessment report of Tanzania (NAFORMA) (URT, 2010). Also, a map on page 50 of Wami/Ruvu Atlas by GLOWS-FIU (2014) was useful in determining the location of wetlands.

After initial LULC classification, the ‘serval’ plugin version 0.8.1 (Pasiok, 2016) was used in QGIS 2.18.4 with the aid of Google Hybrid web plugin to edit the LULC raster file. The editing was necessary to classify some land uses more accurately; for example, the exact size and location of UWAWAKUDA rice farms which was the focus in scenario simulations. Since the raster file contained a lot of cells and that the serval plugin did not appear to have a capability to select multiple cells at a time, an auto clicker (downloaded from http://www.shockingsoft.com/AutoClicker.html) was used to obtain a capability to automatically click many cells per second compared to clicking by hand one cell after another.

Finally, SWAT land use look-up table was prepared in CSV file format. The table comprised of land use ID as per classification in LULC map and a corresponding SWAT land use code (see Table 3).
Description of SWAT land use codes can be found in SWAT input/output documentation (Arnold et al., 2012a) (pp. 566).

**Table 3: Land use look-up table and description of each land use, as used in this study showing land use ID in LULC map with a corresponding SWAT land use code.**

<table>
<thead>
<tr>
<th>Land use ID</th>
<th>SWAT land use code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FRST</td>
<td>Mixed forest</td>
</tr>
<tr>
<td>2</td>
<td>FRSD</td>
<td>Deciduous forest</td>
</tr>
<tr>
<td>3</td>
<td>RNGB</td>
<td>Rangeland and brush land</td>
</tr>
<tr>
<td>4</td>
<td>WATR</td>
<td>Water</td>
</tr>
<tr>
<td>5</td>
<td>WETN</td>
<td>Non-forested Wetland</td>
</tr>
<tr>
<td>6</td>
<td>AGRR</td>
<td>General agriculture</td>
</tr>
<tr>
<td>7</td>
<td>URML</td>
<td>Urban area (medium-low density)</td>
</tr>
<tr>
<td>8</td>
<td>SUGC</td>
<td>Sugar cane</td>
</tr>
<tr>
<td>9</td>
<td>RICE</td>
<td>Rice</td>
</tr>
</tbody>
</table>

Source: (Arnold et al., 2012a) (pp. 566 & 612)

### 3.3.3 Soil map

The soil map (in raster file format) was clipped by using the extent of a study area shapefile. The shapefile was derived from DEM during watershed creation step. The clipped raster file of the soil map was then projected into Arc 1960/UTM Zone 37 S from its original WGS 84 projection.

### 3.3.4 Weather data

**Precipitation**

Rainfall data period ranged from 1/1/2007 to 12/31/2016 and was available from two stations. One from WRBWO’s station at Wami Prison and the other from TMA’s station at SUA. However, the datasets had some gaps. The missing rainfall values were assigned a value of -99.0 as per SWAT input/output documentation by Arnold et al. (2012a)(pp.141). The SWAT will then generate the missing value for a given day (Arnold et al., 2012a)(pp.141). Moreover, percentage of missing rainfall data was calculated for each year from 2007-2016 for the two stations (Table 4 & 5).
Table 4: Missing rainfall data (%) SUA station for 2007-2016 period

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of days</td>
<td>365</td>
<td>366</td>
<td>365</td>
<td>365</td>
<td>366</td>
<td>365</td>
<td>365</td>
<td>365</td>
<td>365</td>
<td>366</td>
</tr>
<tr>
<td>Days with available data</td>
<td>365</td>
<td>366</td>
<td>365</td>
<td>365</td>
<td>366</td>
<td>365</td>
<td>365</td>
<td>335</td>
<td>365</td>
<td>366</td>
</tr>
<tr>
<td>% of missing data</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>8 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
</tbody>
</table>

Table 5: Missing rainfall data (%) at Wami Prison station for 2007-2016 period

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of days</td>
<td>365</td>
<td>366</td>
<td>365</td>
<td>365</td>
<td>366</td>
<td>365</td>
<td>365</td>
<td>365</td>
<td>365</td>
<td>366</td>
</tr>
<tr>
<td>Days with available data</td>
<td>365</td>
<td>366</td>
<td>123</td>
<td>273</td>
<td>297</td>
<td>365</td>
<td>365</td>
<td>365</td>
<td>121</td>
<td>67 %</td>
</tr>
<tr>
<td>% of missing data</td>
<td>0 %</td>
<td>0 %</td>
<td>66 %</td>
<td>25 %</td>
<td>19 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>67 %</td>
</tr>
</tbody>
</table>

Maximum and minimum temperature

Maximum and minimum air temperature was available from one station for the same period as rainfall data (TMA station at SUA in Morogoro). This data was also applied to the second station. Like rainfall, missing temperature values was assigned a value of -99.0.

Relative humidity

Relative humidity (RH) was also available from only one station (TMA station at SUA in Morogoro). This data was also applied to the second station. However, the RH data was available at two different times of a day i.e. 0600z and 1200z. Thus, RH for a given day was calculated as an average between RH recorded at 0600z and 1200z. RH raw values were divided by 100 to convert them into fractions (compatible with SWAT). For example, raw RH data at 0600z on 1/1/2007 read as 69. This was divided by 100 to read as 0.69. Missing RH values were then assigned a value of -99.0.

Wind speed

Wind speed data was also available from only one station (TMA station at SUA in Morogoro). This data was also applied to the second station. Like RH, wind speed record was also available at two different times of a day i.e. 0600z and 1200z. Thus, wind speed for a given day was calculated as an
average between wind speed recorded at 0600z and 1200z. However, wind speed unit was in knots. This was converted to meters per second by multiplying by approximately 0.5 (Wikipedia, 2017).

**Solar radiation**

Solar radiation was also available from only one station (TMA station at SUA in Morogoro). This data was also applied to the second station. Missing solar radiation data were assigned a value of -99.0.

**Troubleshooting with missing values**

The QSWAT model encountered an unknown error on multiple occasions when reading the missing values of solar radiation, wind speed and RH. Eventually, the problem was fixed by filling the missing values by an average value calculated from the available values of preceding dates based on common sense instead of the initially assigned -99.0.

**Customization of SWAT Reference database and weather data files**

A customized SWAT Reference database for the project was created and was used to replace the default one in the project database as demonstrated in a tutorial by Trolle (2016). Customization involved creating and importing a weather generator (WGEN) file containing weather statistics into SWAT Reference database. The WGEN (in Microsoft excel format) and SWAT-compatible weather data files (in text format) were created by using WGEN Parameters Estimation Tool (downloaded from [http://swat.tamu.edu/](http://swat.tamu.edu/)). The tool is very simple to use and user guide details are provided by Essenfelde (2016).

**3.3.5 River flow data**

**Flow at Mandera (outlet of study area)**

Daily flow at Mandera gauging station from 2007-2016 was used as an outlet flow for the study area. The flow data was split into two periods: 2012-2013 for calibration and 2014-2015 for validation (Table 6). The two periods were chosen because they both had less missing data (about 18 % missing) in sequence compared to any other period between 2007-2016.
Table 6: Percentage of missing observed flow data at the watershed outlet (Mandera station) for three periods used in the model

<table>
<thead>
<tr>
<th>Period</th>
<th>Model warm up period</th>
<th>Calibration</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of days</td>
<td>No data</td>
<td>366</td>
<td>365</td>
</tr>
<tr>
<td>Days with available data</td>
<td>No data</td>
<td>258</td>
<td>179</td>
</tr>
<tr>
<td>% of missing data</td>
<td>No data</td>
<td>30 %</td>
<td>51 %</td>
</tr>
</tbody>
</table>

Flow at Dakawa (upstream boundary condition for the study area)

The flow at Dakawa gauging station was used as a point source data to account for the portion of flow that is observed at the Mandera gauging station but not generated from within the study area, thus serves as an upstream boundary condition on the model set up. This idea was recommended by Dennis Trolle (personal communication) and is also pointed out in SWAT documentation by Arnold et al. (2009)(pp. 379). Missing data for the point source discharge were filled by calculating averages of flow in a similar period in preceding year. For example, missing flow data in November 2017 would be filled by an average of flow in November 2016 (in case of whole month missing data). If it is just few days missing in given month, then an average of available data in that month was used to fill the gap. Gap filling was necessary because this point source serves as a boundary condition (Dennis Trolle, personal communication). Also, the point source data was prepared in a format found in ‘ExInputs’ folder in SWAT Editor database. A text file named ‘pointsdaily’ was used as a template. The point source data length was set to be same as that of weather data (i.e. 1/1/2007-12/31/2016).

3.3.6 Visual exploration of rainfall and flow data

An exploratory analysis was performed on rainfall and flow data in order to visualize trends and reasonability of the observed data as mentioned by Daggupati et al. (2015). This was done by plotting graphs (mostly by use of pivot table in Microsoft Excel). The plots included: total annual rainfall for the two stations to visualize differences in precipitation between the years (see Fig. 7), a hydrograph
of observed daily flow data at watershed outlet to visualize duration of high peaks and low flows (see Figure 8), average monthly flow at Mandera (watershed outlet) against that at Dakawa (assumed to be an upstream point source) to see whether there is a reasonable comparison between the two (see Figure 9) and a plot of average total monthly rainfall for the two rainfall stations superposed with average monthly flow at Mandera to see whether there was a realistic seasonal trend between river flow and rainfall (see Figure 10).

**Figure 7:** Total annual rainfall at SUA and Wami Prison station for 2007-2016 period

**Figure 8:** Observed daily flow hydrograph at Mandera station (study site watershed outlet) for 2008-2015
Figure 9: A comparison of average monthly flow data at Mandera and Dakawa (assumed to be an upstream point source) gauging stations.

Figure 10: Seasonal trend of average total monthly rainfall at the two weather stations and average monthly flow at Mandera.
3.4 Model set up

3.4.1 Watershed delineation

The watershed was delineated by using QSWAT version 1.4 as a plugin to QGIS 2.6.1. Different sub basin size thresholds were tried and finally 50 km$^2$ was used because it captured well some tributaries/rivers, which were known to exist at certain locations (e.g. location (coordinates) of Mkindo river was known from a field visit). An outlet was drawn within a threshold of 300 m of a stream at Mandera gauging station (a shapefile with location of gauging station was loaded on the QGIS window). Also, a point source that would represent daily discharge defining a boundary condition between the study area and the rest of the Wami basin was added to the same outlet shape file within proximity of Dakawa gauging station. Watershed was then created after drawing the outlet and point source location. Sub basins with less than 50% of the mean area were selected and merged. Finally, a watershed with 88 sub basins was obtained. Although no information on threshold was given, Wambura et al. (2015) reported dividing entire Wami basin into 45 sub basins. Thus 88 sub basins obtained for this study area can be considered to represent a greater spatial detail.

3.4.2 HRUs creation

Hydrologic Response Units (HRUs) were created next after watershed delineation. User-defined LULC and its associated look-up table and global soils option were used in creation of the HRUs. Slope bands (%) of 0-8, 8-20, 20-30 and >30 were used. The choice of slope bands intended to divide topography into ‘level to gently undulating’ (0-8 %), ‘rolling to hilly’ (8-30 %) and ‘steeply dissected to mountainous’ (>30 %) terrains following the slope classes defined by (FAO, 2003). The HRUs were filtered by land use, soil and slope at a threshold of 5 %, 45 % and 45 % for land use, soil and slope, respectively. A total of 440 HRUs were obtained as a result.

However, efforts to obtain detailed agricultural land use statistics from local authorities were not successful. Therefore, best estimate was made based on literature information, for example Madulu (2005) points out that sugar cane cultivation covered more than 12,000 ha (although this was in 2002) and that maize, sugar cane and rice were among the main crops grown in the Wami basin. Also, as per URT (2012)(pp.28) Mvomero district (most of the study area agricultural land is in this district) had 7.8 % agricultural land under paddy production. Thus, the agricultural land (AGRR) was split into 12 % rice, 82 % AGRR and 6 % sugar cane. This splitting gave 13,173 ha of sugar cane which is close to literature value.
Elevation bands were also included in the model during the HRUs creation. Five bands were created for sub basins whose maximum height exceeds 1500 m above sea level. The elevation bands were included to account for temperature and rainfall variation due to presence of mountains in the study area (Arnold, 2012; pp.127). A temperature lapse rate of -6 °C/km (Arnold, 2012; pp.128) was used. For rainfall, a lapse rate of 500 mm/km was used for sub basin 33, 37 and 41 (location of Nguu mountains) whereas 300 mm/km was used for the rest of the sub basins. The figures on precipitation lapse rate were estimated based on the literature description of the climate of the study area are provided in section 3.1.6.

3.4.3 Editing inputs, QSWAT set up and run

Point source discharge

Point source (whose discharge defines boundary condition between the study area and the rest of the Wami basin) text file was loaded and saved under ‘Edit SWAT inputs’. Then point source files were re-written. An average value calculated from months with available data was used to fill gaps in data for similar months i.e. missing data in missing data in January in given year was filled with an average value calculated from January of another year with complete data. The average values used in months with missing data is shown in Table 7.

**Table 7: Methodology applied in filling in data gaps in the point source data**

<table>
<thead>
<tr>
<th>Month</th>
<th>Year</th>
<th>how the gap was filled (units are in cubic meters per second)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>2009</td>
<td>An average value of 8.92 calculated from observed values of all the months of June was filled in</td>
</tr>
<tr>
<td>10</td>
<td>2010</td>
<td>An average value of 1.71 calculated from observed values of all the months of October was filled in</td>
</tr>
<tr>
<td>10</td>
<td>2011</td>
<td>An average value of 1.71 calculated from observed values of all the months of October was filled in</td>
</tr>
<tr>
<td>12</td>
<td>2011</td>
<td>An average value of 4.23 calculated from observed values of all the months of December was filled in</td>
</tr>
<tr>
<td>8</td>
<td>2014</td>
<td>An average value of 3.02 calculated from observed values of all the months of August was filled in</td>
</tr>
<tr>
<td>6</td>
<td>2015</td>
<td>An average value of 8.92 calculated from observed values of all the months of June was filled in</td>
</tr>
</tbody>
</table>
An average value of 3.43 calculated from observed values of all the months of July was filled in

An average value of 3.02 calculated from observed values of all the months of August was filled in

An average value of 2.76 calculated from observed values of all the months of September was filled in

An average value of 1.84 calculated from observed values from day 10 to day 15 of October was used

Average monthly values calculated from observed values of respective months was filled in

**Watershed data (.bsn)**

The default Penman/Monteith method was used for estimating potential evapotranspiration (IPET) whereas the default soil moisture method was used for estimating daily curve number (ICN).

**SWAT set up and run**

The model run (daily time step) was set from 2007-2013 with 5 years warm up.

**3.5 Model calibration and validation**

**3.5.1 Calibration**

It could be worth mentioning that the model calibration was done twice: initial calibration and recalibration (similarly for validation). After the first calibration and validation process, it was realized that there was a room for potential improvement with a different approach. For clarity, only the recalibration process is described here. The model was recalibrated after it was discovered that there was inconsistency in baseline scenario design i.e. the frequency and total amount of irrigation water (i.e. for crop growth season) used in model calibration was much less than the one used in scenario design. Recalibration was also necessary since the initial model set up did not include elevation bands, but this time the elevation bands were included. To account for uncertainty in the precipitation lapse rate used in the elevation bands, precipitation adjustment parameter was included in the recalibration process; making a total of 19 calibrated parameters (Table 8). Moreover, it was discovered that the point source discharge data was not correctly formatted i.e. the discharge was in original cubic meters per second format instead of cubic meters per day.
Model calibration was done using Soil and Water Assessment Tool Calibration and Uncertainty Programs (SWAT-CUP), version 2012. Within SWAT-CUP, SUFI 2 (Sequential Uncertainty Fitting version 2) algorithm was used for calibration within 95 % prediction uncertainty (95 PPU) as per procedure documented by Abbaspour (2015). SUFI 2 was used because of its capability to combine optimization and uncertainty of parameters at once in addition to its efficiency and ease of implementation (Abbaspour et al., 2004). The SUFI 2 procedure was also well described in the user manual and it was easy to follow the outlined steps. A total of 19 parameters relevant for stream flow calibration were selected (see Table 8). A ‘par_inf.txt’ file containing most of these parameters and their initial ranges was obtained from Eugenio Molina-Navarro (email/personal communication and Molina-Navarro et al. (2017)) and modified accordingly to suit this study with suggestions from Dennis Trolle and Anders Nilsen (personal communication). The calibration period was two years: 2012-2013 at a daily time step.

At first, calibration was set up at a daily time step by using observed weather data. Then different approaches were tried in calibration i.e. daily time step using global weather data from Climate Forecast System Reanalysis (CFSR) downloaded from [https://globalweather.tamu.edu/](https://globalweather.tamu.edu/); then calibration using monthly time step for measured weather data was tried. Different objective functions were also tried to see how the model performance responded. Also, it is pointed out by Abbaspour (2015) (pp. 25) that 200-300 simulation per iteration is acceptable for SUFI 2.

Moreover, parameterization was tried with daily time step approach both for measured and CFSR weather data. Parameterization in this context means grouping parameters into different regions of a watershed as pointed out by Abbaspour (2015, pp.51). In parameterization, the watershed was divided into three regions: one region comprised of sub basins around the main channel and the other two regions comprised of sub basins contributing to each of the two main tributaries in the watershed. Finally, measured weather data was used for calibration because the observed data appeared to result in better model performance than the CFSR data for this study area. Also, parameterization was not adopted in the model calibration because the tests showed that it did not result into better model performance.

After each iteration, new suggested parameter ranges were imported to ‘par_inf.txt’ file using ‘import’ option in SWAT-CUP interface. The newly imported parameter ranges were inspected for reasonability (for example, a negative value of GW_DELAY was considered unrealistic) and corrected accordingly, where necessary, before running a new iteration. The procedure was repeated
until there was no further improvement in the objective function but rather a deterioration in p-factor below recommended value of >70% (Abbaspour, 2015)(pp. 17). A total of 4 iterations with 1000 simulations each were run. The parameter set ranges which produced the 3rd iteration was used to run the 4th iteration. The values of the parameter set from the 4th iteration was used to set the final parameter values in QSWAT files (Abbaspour, 2015, pp.66), which were later used to replace their original uncalibrated versions in the QSWAT model ‘TxtInOut’ directory.

Table 8: Selected parameters, method of change and initial maximum and minimum uncertainty ranges

<table>
<thead>
<tr>
<th>#</th>
<th>Parameter name and its file extension</th>
<th>Method of change</th>
<th>Range of values</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CN2.mgt</td>
<td>Relative</td>
<td>-0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>2</td>
<td>SURLAG.bsn</td>
<td>Value</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>ALPHA_BF.gw</td>
<td>Value</td>
<td>0</td>
<td>1.011</td>
</tr>
<tr>
<td>4</td>
<td>ALPHA_BF_D.gw</td>
<td>Value</td>
<td>0</td>
<td>1.011</td>
</tr>
<tr>
<td>5</td>
<td>ALPHA_BNK.rte</td>
<td>Value</td>
<td>0</td>
<td>1.1</td>
</tr>
<tr>
<td>6</td>
<td>CH_K2.rte</td>
<td>Value</td>
<td>0</td>
<td>150</td>
</tr>
<tr>
<td>7</td>
<td>EPCO.hru</td>
<td>Value</td>
<td>0.01</td>
<td>1.103</td>
</tr>
<tr>
<td>8</td>
<td>ESCO.hru</td>
<td>Value</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>GWQMN.gw</td>
<td>Value</td>
<td>0</td>
<td>2000</td>
</tr>
<tr>
<td>10</td>
<td>GW_DELAY.gw</td>
<td>Value</td>
<td>0</td>
<td>600</td>
</tr>
<tr>
<td>11</td>
<td>GW_REVAP.gw</td>
<td>Value</td>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>12</td>
<td>OV_N.hru</td>
<td>Relative</td>
<td>-0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>13</td>
<td>REVAPMN.gw</td>
<td>Value</td>
<td>0</td>
<td>2000</td>
</tr>
<tr>
<td>14</td>
<td>SOL_AWC(..).sol</td>
<td>Relative</td>
<td>-0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>15</td>
<td>SOL_BD(..).sol</td>
<td>Relative</td>
<td>-0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Parameter set ranges which produced the last best iteration in the recalibration process was used to run 1 iteration for validation. As it was for recalibration process, the same 1000 simulations per iteration were run for validation. However, SWAT CUP files were edited accordingly to reflect time and observation data for validation period as per user manual by Abbaspour (2015). The validation period was two years: 2014-2015 at a daily time step like calibration.

3.6 Model performance evaluation

3.6.1 Evaluation methods

Although graphical methods is among the recommended hydrological model evaluation methods, it has some limitations e.g. it does not quantify model performance and therefore needs to be complemented with statistical methods to obtain quantitative model performance (Moriasi et al., 2015). There are 10 different statistical measures referred to as objective functions currently included in the SWAT-CUP manual (Abbaspour, 2015)(pp. 55) to choose from for model calibration and validation. A Literature review during this study indicated that Nash-Sutcliffe efficiency (NSE) was the most commonly used objective function in model calibration and validation. Also, a meta-analysis by Moriasi et al. (2015) reveals that coefficient of determination ($R^2$), Nash-Sutcliffe efficiency (NSE) and percent bias (PBIAS) are the most widely reported model evaluation criteria. For this reason, NSE was used as an objective function in this study to calibrate and validate the model due to sufficient availability of reported values for ease of comparison of this study to other studies.

3.6.2 Recommended model performance thresholds

A study by Moriasi et al. (2015) has recommended new model performance measures based on a review of numerous published works (most up to date work compared to a similar study by Moriasi et al. (2007)). The new recommended thresholds for which the model performance whether for daily,
monthly or annual stream flow, can be rated as ‘satisfactory’ if: $R^2 > 0.60$, $NSE > 0.50$ and $PBIAS \leq \pm 15\%$, for watershed-scale models.

### 3.6.3 Advantages and limitations of selected statistical evaluation methods

Each objective function has its advantages and limitations therefore the NSE was combined with $R^2$ and PBIAS in line with recommendation of Krause et al. (2005) for a combined use of multiple efficiency criteria along with a measure of absolute or relative volume error. P-factor and r-factor were also included in the model to quantify the percentage of observed data covered within 95 PPU and the uncertainty range for predictions, respectively (Abbaspour, 2015)(pp.17).

The $R^2$ is defined as “squared ratio between the covariance and the multiplied standard deviations of the observed and predicted values” (Krause et al., 2005) and has values between 0 and 1, where 1 indicates perfect correlation between observed and simulated data and 0 indicates complete lack of correlation between observed and simulated data (Krause et al., 2005). The main limitation of $R^2$ is reported to be its tendency to give good values close to 1 for models which systematically and consistently over predict or under predict flows albeit all predictions were false.

The NSE is obtained by subtracting the summation of absolute squared differences between observed and predicted values that have been normalized by the variance of observed values for simulation period from 1. The NSE has values between 1 and $-\infty$ with 1 indicating perfect match between observed and simulated values whereas a value of $0 <$ indicates that mean of the observed data is a better predictor compared to the model. Major weakness of NSE lies in its tendency to overestimate and underestimate model performance during peak flows and low flows, respectively. This limitation originates from normalization of the variance of observed data and squaring of the differences between observed and simulated data (Krause et al., 2005).

According to Gupta et al (1999) (as cited by Moriasi et al. (2007)), PBIAS (percent bias) measures the average tendency of the model to overestimate or under estimate simulated data compared to observed data. Values of PBIAS range between negative and positive values whereby 0.0 indicates optimal model performance. Values of low magnitude indicate accurate model performance, with positive values indicating model underestimation and negative values indicating model over estimation. Poor model performance can easily be identified from PBIAS as pointed out Gupta et al (1999) (as cited by Moriasi et al. (2007)), and is thus recommended in quantification of water balance errors in hydrological models (Moriasi et al., 2007).
3.7 Scenarios design

3.7.1 Conventional rice cultivation (CRC) scenario

This scenario involves continuous flooding method as currently done at UWAWAKUDA rice farms. Management file was edited to reflect the normal (baseline scenario used in model calibration) management operations at the rice farms as shown in Table 9. The edits were done in sub basin: 52 (large portion of rice farm is in this sub basin), land use: RICE, soil: Vp50-3a-968 and slope: 0-8 as shown in Figure 11. As per FAO (2003), Vp50-3a is a soil mapping unit representing fine-textured Pellic Vertisol with over 35 % clay and slope between 0-8 %. The rice farms in this sub basin represent an HRU of 17 km$^2$ out 20 km$^2$ of the entire UWAWAKUDA rice farms. The rice is sometimes broadcast, but is often transplanted. Therefore, to account for transplanted rice, initial land cover was set to: Rice, initial plant leaf area index (LAI) = 3. Literature search for LAI of 21 days old rice seedlings was not successful, so the LAI of 3 was selected because it resulted in a rice yield of around 4 t/ha (i.e. average of observed yields as per interview during field visit). Initial dry weight biomass was set to 120 kg/ha (an estimate based on the amount seed requirement per hectare documented in literature e.g. Stoop et al. (2002)).
Figure 8: A screenshot of a SWAT Editor showing a portion of baseline management operation file and sub basin number, soil type and slope in which the management operations were defined.
Table 9: Year 1 operations for CRC and SRI scenarios at Dakawa rice farms during wet season (the exact dates may vary)

<table>
<thead>
<tr>
<th>Date</th>
<th>Operation</th>
<th>Scenario</th>
<th>CRC Irrigation amount (mm)</th>
<th>SRI Irrigation amount (mm)</th>
<th>Control Irrigation amount (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
<td>Day</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Tillage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>Irrigation</td>
<td>10</td>
<td>10</td>
<td>None</td>
</tr>
<tr>
<td>2</td>
<td>28</td>
<td>Fertilizer application (DAP:124 kg/ha)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Transplanting/beginning of growing season (15 days old seedlings)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Irrigation</td>
<td>10</td>
<td>10</td>
<td>None</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>Irrigation</td>
<td>10</td>
<td>10</td>
<td>None</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>Fertilizer application (Urea: 124 kg/ha) (tillering stage- 30 days old rice since germination)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>21</td>
<td>Irrigation</td>
<td>10</td>
<td>10</td>
<td>None</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>Irrigation</td>
<td>50</td>
<td>50</td>
<td>None</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>Irrigation</td>
<td>100</td>
<td>50</td>
<td>None</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>Irrigation</td>
<td>100</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>Fertilizer application (Urea:124 kg/ha) (panicle formation stage)-60 days after germination</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>21</td>
<td>Irrigation</td>
<td>100</td>
<td>50</td>
<td>None</td>
</tr>
</tbody>
</table>
Several assumptions were made for scenario in Table 9: The rice is transplanted at the same date (1st March for wet season, 1st August for dry season; growing season lasts for four months) for all 1,700 ha (17 km²), a given amount of irrigation water (in mm) is applied for all 1,700 ha and irrigation is done for days where there is no-/insufficient rainfall. Since rice cultivation at UWAWAKUDA rice farms is done during wet season, it can thus be assumed that irrigation frequency is low and less predictable, hence for simplicity purpose of this study, approximate irrigation interval of 7 days was adopted. The 7-day interval was adopted based on the interview findings during field visit to Mkindo irrigation scheme. The scenario was simulated for both wet (Table 9) and dry (Table 10) season to account for any masking effect caused by wet season on the response of variables of interest. Also, from interview and personal observation during field visit, the level of water in the river was most challenging to grow rice in dry season as shown in Figure 12.

Both scenarios were simulated at annual time step from 2012-2015. Warm up period was 2007-2011.
The variables of interest included average annual amount of irrigation water applied, average annual rice yield, average annual GWQ, average annual ET and average annual SURQ. The GWQ is defined as “ground water contribution to stream in watershed on day, month or year (mm)”, ET is defined as “actual evapotranspiration in watershed for the day, month or year (mm)” and SURQ is defined as “surface runoff generated in watershed for the day, month or year (mm)” (Arnold et al., 2012a)(pp. 440). The GWQ, ET and SURQ were selected because they are important components of water balance in the watershed as illustrated by (Arnold et al., 2009) (pp. 9). Additionally, water stress, nitrogen stress, phosphorus stress and temperature stress were also noted for each scenario in the specific HRU.

Two irrigation sources were tried during scenario simulations i.e. sub basin 67 which was closest to the actual location of water intake for UWAWAKUDA rice farms and an unlimited source outside

**Figure 9: A section of the Wami River near UWAWAKUDA rice farms showing irrigation intake canal and water level in the River as observed during field visit on February 16, 2017**
the watershed. The management operations for dry season included in the QSWAT model are shown in Table 10.

**Table 10: Management operations for CRC, SRI and Control scenarios during dry season simulated for UWAWAKUDA rice farms (the dates are tentative except for the season)**

<table>
<thead>
<tr>
<th>Date</th>
<th>Operation</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
<td>Day</td>
<td>CRC Irrigation amount (mm)</td>
</tr>
<tr>
<td>7</td>
<td>25</td>
<td>Tillage</td>
</tr>
<tr>
<td>7</td>
<td>30</td>
<td>Irrigation</td>
</tr>
<tr>
<td>7</td>
<td>31</td>
<td>Fertilizer application (DAP)</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>Transplanting/beginning of growing season (15 days old seedlings)</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>Irrigation</td>
</tr>
<tr>
<td>8</td>
<td>14</td>
<td>Irrigation</td>
</tr>
<tr>
<td>8</td>
<td>15</td>
<td>Fertilizer application (Urea) (tillering stage- 30 days old rice since germination)</td>
</tr>
<tr>
<td>8</td>
<td>21</td>
<td>Irrigation</td>
</tr>
<tr>
<td>8</td>
<td>30</td>
<td>Irrigation</td>
</tr>
<tr>
<td>9</td>
<td>7</td>
<td>Irrigation</td>
</tr>
<tr>
<td>9</td>
<td>14</td>
<td>Irrigation</td>
</tr>
<tr>
<td>9</td>
<td>15</td>
<td>Fertilizer application (Urea) (panicle formation stage)-60 days after germination</td>
</tr>
<tr>
<td>Date</td>
<td>Days after germination</td>
<td>Irrigation activity</td>
</tr>
<tr>
<td>------</td>
<td>-----------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>9</td>
<td>21</td>
<td>Irrigation</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>Irrigation</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>Irrigation</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>Irrigation-90 days after germination</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>15</td>
<td>Harvest and kill operation</td>
</tr>
</tbody>
</table>

### 3.7.2 SRI scenario

In this scenario, the maximum amount of irrigation water applied was 50 mm per irrigation event. The irrigation was scheduled to take place after every 7 days as per interview with SRI farmers in Mkindo area. Mkindo is a name of a locality within the study area where there is rice irrigation scheme (Figure 13) involving the SRI. The SRI rice takes about 97 days to be ready for harvest as per interview with the farmers. The SRI scenario was simulated both for rice grown in wet (transplanting on 1st March) and dry (transplanting on 1st August) season. This was important to account for possibility of effect of irrigation on variables of interest being masked by wet season. Also, it was important to see how the SRI would perform during dry season when the water availability is most challenging in the river as per personal observation and interview with the chairman of UWAWAKUDA rice farms. The management operations for wet and dry season included in the QSWAT model are shown in Table 9 and Table 10, respectively.
Figure 10: Water intake for Mkindo irrigation scheme as observed during field visit on February 8, 2017. Weirs are encircled in red.

3.7.3 Control scenario

The control scenario (no irrigation scenario) was included to be used as a reference for CRC and SRI scenarios. Here no any amount of irrigation water was applied. Like other scenarios, ‘no irrigation’ was also simulated for both wet and dry season and response of variables of interest was recorded from HRU output summary in QSWAT.

3.7.4 Actual amount of water abstracted from the river for rice irrigation

The water abstraction permit for cooperative of Dakawa rice farms allows a maximum of 5 m$^3$/s (Tumaini Lyamongo, personal communication). This amount is abstracted for about four months (rice growing season) (interview with Tomas P. Kakema). If this amount of water is abstracted each day for a growing season of four months, then the total water use will be:

$$5 \text{ m}^3/\text{s} \times \left(60 \times 60 \times 24 \times 30 \times 4\right) \text{s} = 51,840,000 \text{ m}^3$$

Since the rice farms cover an area of 2,000 ha (2,000 × 10,000 m$^2$), then total irrigation amount for the 2,000 ha (20 km$^2$) is:

$$51,840,000 \text{ m}^3 / 20,000,000 \text{ m}^2 = 2.592 \text{ m}^3/\text{m}^2 \text{ (equivalent to 2592 mm)}$$
The calculated total irrigation amount of 2592 mm is undoubtfully realistic as it agrees with the highest mean irrigation amount (2820 mm) for CRC reported by Kahimba et al. (2014). However, the calculated amount does not account for water losses for example due to canal conveyance inefficiencies such as seepage (Santhi et al., 2005 ) which might be a strong possibility as it was observed that most of the irrigation canals were not paved (Figure 14) although the paving was underway during field visit for this study as shown in Figure 15. If water losses are accounted for, the actual total irrigation water will likely be less than 2.592 m$^3$/ m$^2$.

\textit{Figure 11: Unpaved portion of main irrigation canal at UWAWAKUDA rice farms as observed during field visit on February 16, 2017.}
Figure 12: Paved portion of main irrigation canal at UWAWAKUDA rice farms as observed during field visit on February 16, 2017.
4.0 Results

4.1 Model calibration and validation

Results for calibrated model parameter ranges are presented in Table 1. The results of calibration for visual interpretation of model performance is presented in form of hydrograph shown in Figure 17. Similar hydrograph for model validation is shown in Figure 18. Results of selected statistical criteria for objective evaluation of model performance are presented in Table 12.

Table 11: Final model parameter value ranges and fitted values (based on the best simulation) within 95 PPU.

<table>
<thead>
<tr>
<th>Parameter_Name</th>
<th>Method of change</th>
<th>Fitted_Value</th>
<th>Min_value</th>
<th>Max_value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: R__CN2.mgt</td>
<td>relative</td>
<td>-0.223941</td>
<td>-0.350025</td>
<td>0.021357</td>
</tr>
<tr>
<td>2: V__SURLAG.bsn</td>
<td>value</td>
<td>5.708704</td>
<td>3.594361</td>
<td>8.483015</td>
</tr>
<tr>
<td>3: V__ALPHA_BF.gw</td>
<td>value</td>
<td>0.532901</td>
<td>0.414647</td>
<td>0.830301</td>
</tr>
<tr>
<td>4: V__ALPHA_BF_D.gw</td>
<td>value</td>
<td>0.39923</td>
<td>0.295136</td>
<td>0.59995</td>
</tr>
<tr>
<td>5: V__ALPHA_BNK.rte</td>
<td>value</td>
<td>1.026571</td>
<td>0.883998</td>
<td>1.636362</td>
</tr>
<tr>
<td>6: V__CH_K2.rte</td>
<td>value</td>
<td>14.406343</td>
<td>0</td>
<td>55.730537</td>
</tr>
<tr>
<td>7: V__EPCO.hru</td>
<td>value</td>
<td>0.560229</td>
<td>0.273128</td>
<td>0.819466</td>
</tr>
<tr>
<td>8: V__ESCO.hru</td>
<td>value</td>
<td>0.317833</td>
<td>0</td>
<td>0.387838</td>
</tr>
<tr>
<td>9: V__GWQMN.gw</td>
<td>value</td>
<td>675.827759</td>
<td>304.523163</td>
<td>913.718567</td>
</tr>
<tr>
<td>10: V__GW_DELAY.gw</td>
<td>value</td>
<td>128.264175</td>
<td>0</td>
<td>228.838852</td>
</tr>
<tr>
<td>11: V__GW_REVAP.gw</td>
<td>value</td>
<td>0.110766</td>
<td>0.104971</td>
<td>0.217503</td>
</tr>
<tr>
<td>12: R__OV_N.hru</td>
<td>relative</td>
<td>0.101136</td>
<td>0.073733</td>
<td>0.277475</td>
</tr>
<tr>
<td>13: V__REVAPMN.gw</td>
<td>value</td>
<td>3168.989258</td>
<td>1834.030151</td>
<td>3661.489746</td>
</tr>
<tr>
<td>14: R__SOL_AWC(..).sol</td>
<td>relative</td>
<td>1.32904</td>
<td>0.463873</td>
<td>1.691931</td>
</tr>
<tr>
<td>15: R__SOL_BD(..).sol</td>
<td>relative</td>
<td>0.002272</td>
<td>-0.028636</td>
<td>0.18675</td>
</tr>
<tr>
<td>16: R__SOL_K(..).sol</td>
<td>relative</td>
<td>1.775669</td>
<td>0.945238</td>
<td>2.158432</td>
</tr>
<tr>
<td>Parameter</td>
<td>Type</td>
<td>Value 1</td>
<td>Value 2</td>
<td>Value 3</td>
</tr>
<tr>
<td>-----------</td>
<td>------------</td>
<td>---------------</td>
<td>---------------</td>
<td>---------------</td>
</tr>
<tr>
<td>V__CH_K1.sub</td>
<td>value</td>
<td>57.785412</td>
<td>34.16227</td>
<td>72.542679</td>
</tr>
<tr>
<td>V__RCHRG_DP.gw</td>
<td>value</td>
<td>0.405758</td>
<td>0.333308</td>
<td>0.63965</td>
</tr>
<tr>
<td>R__PRECIPI..(..){..}.pcp</td>
<td>relative</td>
<td>-0.03454</td>
<td>-0.308215</td>
<td>0.197187</td>
</tr>
</tbody>
</table>

**Figure 17:** Model calibration hydrograph showing observed daily flow, best estimation and 95 PPU envelope
Figure 18: Model validation hydrograph showing observed daily flow, best estimation and 95 PPU envelope

Table 12: Results of selected statistical criteria for evaluating the performance of model calibration and validation.

<table>
<thead>
<tr>
<th></th>
<th>Calibration</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-factor</td>
<td>0.93</td>
<td>0.45</td>
</tr>
<tr>
<td>r-factor</td>
<td>1.49</td>
<td>1.27</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.77</td>
<td>0.51</td>
</tr>
<tr>
<td>NSE</td>
<td>0.76</td>
<td>0.50</td>
</tr>
<tr>
<td>PBIAS</td>
<td>-13.7</td>
<td>3.8</td>
</tr>
</tbody>
</table>
4.2 Scenario simulations

4.2.1 Effect of SRI on rice yield

The impact of SRI on rice yield is shown in Figure 19 and Figure 20. For example: response of rice yield to simulated irrigation scenarios for both wet and dry season by using irrigation source from within the watershed is shown in Figure 19 whereas the response of rice yield to simulated irrigation scenarios by using unlimited water supply from outside the watershed during a dry season is shown in Figure 20.

The reader’s attention is called on to two areas: firstly, to the differences in yield between rice cultivation methods/scenarios i.e. Control, SRI and CRC within the season and between the seasons (wet season denoted as ‘WET’ and dry season denoted as ‘DRY’) (Fig. 19). Secondly, to the differences in rice yield between the cultivation methods/scenarios during dry season with different sources of irrigation water i.e. from the watershed (denoted as ‘INSIDE’) and from an unlimited source outside the watershed (denoted as ‘OUTSIDE’) (Fig. 20).
**Figure 19:** Yield difference between CRC and SRI for both wet and dry season with irrigation water sourced from within the watershed.
Figure 20: Yield difference between CRC and SRI for dry season with irrigation water sourced from a source inside the watershed and an unlimited source outside the watershed

4.2.3 Effect of SRI on GWQ, ET and SURQ

Response of water balance components (only for irrigation source from within the watershed) to simulated irrigation scenarios are presented in Figure 21 for GWQ, Figure 22 for ET and Figure 23 for SURQ. As defined earlier, GWQ means “ground water contribution to stream in a on day, month or year (mm)”, ET means “actual evapotranspiration in watershed for the day, month or year (mm)” and SURQ means “surface runoff generated in watershed for the day, month or year (mm)” (Arnold et al., 2012a) (Pp. 440). However, in this case the time means a year and spatial detail is at specific HRU level (UWAWAKUDA rice farms) instead of a watershed level since the scenarios were
simulated on a yearly time step at the specific HRU level. The reader’s attention is called on to how these components differ between the simulated scenarios both within a season and between the seasons (wet season is denoted as 'WET' and dry season is denoted as 'DRY').

**Figure 21:** Difference in ground water contribution to stream in the specific HRU in a year (GWQ) between the CRC and SRI for both wet and dry season.
Figure 22: Difference in actual evapotranspiration in the specific HRU in a year (ET) between the CRC and SRI for both wet and dry season.

Figure 23: Difference in surface runoff generated in the specific HRU in a year (SURQ) between the CRC and SRI for both wet and dry season.
4.2.4 Stress factors for the simulated scenarios

Stress factors such as water, nitrogen, phosphorus and temperature stress that could potentially affect the rice yield are presented in Table 13.

Table 13: Irrigation amount and different stresses affecting rice yield for each of the simulated scenarios the specific HRU

<table>
<thead>
<tr>
<th>Variable</th>
<th>Wet season</th>
<th>Dry season</th>
<th>Dry_out</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specified irrigation (mm)</td>
<td>NoIRR 690</td>
<td>NoIRR 690</td>
<td>CRC 690</td>
</tr>
<tr>
<td>Applied irrigation (mm)</td>
<td>NoIRR 597</td>
<td>NoIRR 114</td>
<td>CRC 690</td>
</tr>
<tr>
<td>Water stress (days)</td>
<td>16 9 9 75 42 13</td>
<td>0.12 1.11 1.1 1.6 2.3 2.82</td>
<td>0.45 0.45 0.45 0.71 0.71 0.71</td>
</tr>
<tr>
<td>Nitrogen stress (days)</td>
<td>0 0 0 0 0 0</td>
<td>0 0 0 0 0</td>
<td>0 0 0 0 0 0</td>
</tr>
<tr>
<td>Phosphorus stress (days)</td>
<td>0.45 0.45 0.45 0.71 0.71 0.71</td>
<td>0 0 0 0 0 0</td>
<td>0 0 0 0 0 0</td>
</tr>
<tr>
<td>Temperature stress (days)</td>
<td>0.45 0.45 0.45 0.71 0.71 0.71</td>
<td>0 0 0 0 0 0</td>
<td>0 0 0 0 0 0</td>
</tr>
</tbody>
</table>
5.0 Discussion

This chapter is organized in the following order: the calibration and validation results are discussed first in relation to published guidelines of model performance evaluation and study objectives. Here the performance and suitability of the model for intended application is assessed along with discussion on possible reasons (uncertainties) associated with the observed model performance. Next, the results of scenario simulations are discussed. Here the discussion is based on the presence or absence of differences between the simulated CRC and SRI scenarios. The results are also discussed with relation to findings of other studies (both experimental and modelling studies) and interview findings during field visit. The last part of the chapter will discuss meaning and implications of scenario results in relation to the water saving potential of the SRI and its impact on rice yield, sustainability of rice cultivation in the study area, recommended minimum river flow and downstream water users.

5.1 Performance of model calibration and validation

5.1.1 Graphical evaluation of model performance

From the hydrographs, it can be deduced that the model satisfactorily reproduces the observed trends in daily stream flow during calibration period compared to during validation period. Most of the observations appear to be covered within the 95 PPU for calibration period (Fig. 17). However, the validation hydrograph (Fig. 18) shows that fewer observations are covered within the 95 PPU compared to the calibration hydrograph. Both Fig. 17 and Fig. 18 show that it is difficult to discern from the hydrographs overall flow over- or underestimation because in some parts there is overestimation while in some parts there is underestimation, thus a need for a statistical method.

5.1.3 Model performance against recommended statistical thresholds

The $R^2 = 0.77$ and $\text{NSE} = 0.76$ suggests that the model performance is good whereas the $\text{PBIAS} = -13.7\%$ suggests that the model performance is satisfactory for the calibration period as per Moriasi et al (2015). Performance statistics for model validation indicate somewhat lower model performance with $R^2 = 0.51$, $\text{NSE} = 0.50$. However, $\text{PBIAS} = 3.8\%$ suggests that model performance is very good during validation as per Moriasi et al (2015). These model calibration and validation statistics highlight the importance of using multicriteria performance measures in model evaluation as recommended by Krause et al. (2005). For example, the values of $R^2$ and NSE show that the model is somewhat underperforming during validation period whereas the value of PBIAS shows that the model is performing satisfactorily during calibration but ‘very good’ during validation period.
This difference in model performance between validation and calibration period has commonly been reported in numerous studies as found by Moriasi et al. (2015) in their meta-analysis. Model performance is also reported to decrease with increasing temporal resolution (annual>monthly>daily). This was also the case for this study as monthly time step calibration (monthly results are not included in this report) showed ‘very good’ performance compared to daily time step.

P-factor and r-factor quantify the model prediction uncertainty. As previously stated, the p-factor quantifies the percentage of observed data covered within 95 PPU envelope whereas the r-factor quantifies the uncertainty range for predictions (Abbaspour, 2015)(pp.17). Although no any recommendation was made by Moriasi et al. (2015) on threshold values of p-and r-factor, the p-factor = 0.93 % achieved in model calibration is well above the minimum of > 70 %, and r-factor = 1.49 is somewhat close to a values of around 1 suggested by Abbaspour (2015, pp.17). Model uncertainty range is slightly smaller (r-factor = 1.27) during validation compared to calibration period, however, less observations are covered within the 95 PPU envelope (p-factor = 0.45) as a result. This is common as Abbaspour (2015, pp.18) point out that the value of p-factor becomes smaller as the r-factor gets smaller.

5.1.4 Possible sources of uncertainties associated with the observed model performance

Abbaspour (2015) (pp. 9-12) described and grouped model calibration uncertainties into three groups namely conceptual uncertainties, input uncertainties and parameter uncertainties. Simplifications in the model has been pointed out as one of the sources of conceptual uncertainty. In this study for example, despite the huge size of the watershed, a simple calibration strategy was adopted as opposed to complex calibration strategy recommended by Daggupati et al. (2015). The use of time series of stream flow data at the watershed outlet (as it is the case for this study, not to mention the short calibration period and missing data) to calibrate the model was cited as an example of a simple strategy. A complex strategy on the other hand is described to involve multi-site calibration approach; starting calibration from upstream to downstream sub basins. This approach is recommended for watersheds where there is large variation in characteristics of the study area or when data availability allows. Significant variation in biophysical characteristics in the study area are evident e.g. by looking at the topography, land use/land cover and soil map (see section 3.1).

Another conceptual model uncertainty described by Abbaspour (2015), which might be relevant for this study, is uncertainties arising from processes known to be occurring in the watershed but are not
included in the model. For example, intermittent floodplains are known to exist in the study area. However, the model handles the effects of flooding only very crudely (Dennis Trolle and Anders Nielsen, personal communication).

Furthermore, Abbaspour (2015, pp. 11), describe uncertainties arising from processes which are neither known to the modeler nor are they included in the model. For example, in Figure 10 (see section 3.3.6), there appears to be some rainfall in October-December period but the stream flow trend does not follow that of precipitation as it does during the rest of the year. From literature e.g. Kahimba et al. (2014) the study area is known to receive a bimodal rainfall, with low rains during October-December and high rains during March-May. Therefore, it is uncertain why the stream flow appears to be very low despite the rains. It could be due to errors in stream flow measurements or processes that are completely unknown to the modeler. However, one possible explanation could be that the stream flow response to rainfall is delayed due to surface runoff lag (SURLAG) and ground water delay (GW_DELAY) as shown in Table 11 (see section 4.1) since the months of July, August and September were dry prior to the October rains.

Lastly but not least, input uncertainties are described as those arising from errors in input data. Rainfall and temperature data were pointed out as specific examples because they are measured as point data but used in a distributed watershed. In this study for example, only two weather stations were used. In fact, the rainfall data was from two stations but the rest of the weather parameters were from a single station. This is likely to have introduced considerable uncertainty in model performance because of questionable representativeness of weather data especially in this large watershed in which biophysical variation is evident. For example, there are mountains with altitude of over 2000 m above sea level in the study area and Abbaspour (2015, pp.12) cautions that input uncertainty could be large in mountainous regions. Ten weather stations with data from CFSR was tried but the model performance was even worse, suggesting that the observed data was more representative than the remotely sensed CFSR data under the conditions of this model for this study area. Moreover, use of satellite image and methods used in classification of the image into different land uses and land covers could also be the source of input uncertainties.

5.1.5 Judgement of model suitability for scenario simulations

In view of the discussed model performance and uncertainties associated with it; the important question is now whether this model is adequate for the intended application. The answer can be found by firstly looking at whether the model has unacceptable performance statistics. As per guidelines by
Moriasi et al. (2015), a model with NSE < 0.0, $R^2 < 0.18$ and PBIAS ≥ 30 % is considered unacceptable. Thus, the model used in this study has acceptable performance. Secondly, we can look at the nature of intended model application. Daggupati et al. (2015) point out that the desired level of accuracy and precision in model calibration depends on the designated end use of the model. They define accuracy as “the degree to which the model can correctly simulate the response variable” and precision as “the smallest difference in response variables that the model can correctly differentiate”. Taking Daggupati et al.’s (2015) point of view into account, the intended model application for this study and the fact that model performance is normally much better at monthly and annual time steps than daily, the calibrated model can be judged as satisfactory. This is because the intended model use is for evaluating water balance and rice yield over a rice growing period (as opposed to day to day flow dynamics) and the PBIAS between the simulated and observed river flow has shown that the model is satisfactory for this purpose. The PBIAS is a focus because it measures the overall tendency of the model to overestimate or underestimate the simulated flow against the observed flow as pointed out by Gupta et al (1999) (as cited by Moriasi et al. (2007)).

The model in this study can be considered to provide a better description of the hydrology of the study area compared to that of Wambura (2015) for two main reasons. Firstly, the size of the study area used in this model is about 1/3 of the one used by Wambura et al (2015) and the calibration and validation process used flow data from two gauging stations as opposed to just one station used by Wambura et al (2015). Secondly, the model evaluation in this study adopted one graphical criteria (hydrograph) and three objective criteria (NSE, $R^2$ and PBIAS) as opposed to that of Wambura et al (2015) that adopted two graphical criteria (hydrograph and scatter plots) and one objective criteria only (NSE). Graphical methods are not capable of quantifying model performance as pointed out by Moriasi et al. (2015), hence they can be subjective. For example, in this study the model had NSE = 0.76, $R^2 = 0.77$ and PBIAS = -13.7 % whereas for Wambura et al (2015), the model had NSE = 0.69 for calibration period but no other statistics. For validation period, the model in this study had NSE = 0.50, $R^2 = 0.51$ and PBIAS = 3.8 % whereas that in Wambura et al (2015) had NSE = 0.76 with no further statistics.

5.2. CRC vs. SRI scenario performance regarding water consumption and rice yield

5.2.1 Response of rice yield to irrigation scenarios

The results of scenario simulations convey interesting information. Firstly, there does not appear to be any noticeable difference in rice yield between CRC and SRI method regardless of a wet or dry
season (Fig. 19). To check whether there is any impact of irrigation at all, the control scenario in which no irrigation was applied was simulated. Interestingly, the rice yield was about 357 kg (about 8 %) lower compared to either SRI or CRC during wet season. However, during the dry season, the difference between control and the CRC or SRI is about 1300 kg (about 35 %), clearly suggesting that there was an impact of irrigation but is most pronounced during dry season. This is in agreement with observation from Kahimba et al. (2014) that irrigation water use effect may not be noticeable in wet season.

Although no noticeable difference in yield between the CRC and SRI, the results show that the rice yield during dry season is about 900 kg (20 %) lower than that of wet season with irrigation water sourced from within the watershed (Fig. 19). This difference in rice yield between the seasons prompted a hypothesis that perhaps a limited availability of irrigation water during dry season was limiting optimal rice (paddy) growth. To test this hypothesis, same amount of irrigation water used in previous scenarios was sourced from outside the watershed. According to Arnold et al. (2012a)(pp. 252), SWAT model considers the water diverted from outside the watershed to be unlimited. The results appear to confirm the hypothesis as the rice yield for irrigation sourced from outside was higher by about 1800 kg (about 32 %) compared to the yield where irrigation was sourced from within the watershed (Fig. 20). The hypothesis is also confirmed by the amount of average annual irrigation water applied (in the model output summary) and the total amount of irrigation water applied as per management schedule. For example, in Table 13 (see section 4.2.4), a total of 690 mm and 390 were applied for entire crop growth season as per management schedule but in the model output summary the applied amount appeared to be 114 mm each for CRC and SRI. Furthermore, Table 13 shows that the insufficient irrigation water is also reflected by water stress which is 23 days for the CRC and 11 days for the SRI (dry season) with irrigation water from outside the watershed but about 42 days both for the CRC and SRI with irrigation water from within the watershed. The limited water availability simulated by the model during dry the season corroborates what was reported by Kiwango et al. (2015) that river flow during dry season was observed to be about 30 % lower than the minimum recommended amount. The low river flow was also observed during field visit as shown in Figure 13 (see section 3.7.1).

It is perhaps worth pointing out that the specified total amount of irrigation water (690 mm and 390 mm) in the scenarios design is much lower than the amount required in practice due to the low frequency of irrigation in the scenarios (7-day interval). For example, the irrigation water abstraction from the Wami River as per permit from WRBWO is 2592 mm (before losses are accounted for).
Experimental results from within the study area by Kahimba et al. (2014) show that the highest mean irrigation amount (wet and dry season) for CRC was around 2820 mm and around 1000 mm for SRI. Moreover, average annual potential evapotranspiration in the rice/paddy farms was simulated to be 1343 mm, suggesting that the irrigation amount of 690 mm and 390 mm used in the scenarios design was not enough to meet the evapotranspiration demand. However, although these amounts maybe site specific, they indicate that 690 mm and 390 mm may have been too low for optimal rice growth. The overall interesting thing from these results is the fact that about 44 % water saving can be achieved without any significant reduction in rice yield. These results agree with experimental results by Kahimba et al. (2014) in Tanzania (Mkindo area which is within the watershed of this study). The study revealed up 64 % by SRI at 3-day alternate wetting and drying interval although the study involved manipulation of other agronomic practices such as plant spacing besides irrigation ponding depth. As it can be noted from Jagannath et al. (2013), there is more to SRI practice than just irrigation water management. Meanwhile, experimental study by Tejendra et al. (2011) in Japan achieved 29 % water saving by SRI method at a ten day interval of alternate wetting and drying without significant decrease in yield. Jung et al. (2014) (modelling study using SWAT-APP) reported between 17 to 69 % water saving. A meta-analysis by Jagannath et al. (2013) reported an average of 22 % water saving. It is interesting to learn that this model, with its uncertainties, agrees with results of experimental studies as well as other modelling studies although specific environmental conditions of the study areas need to be considered.

5.2.2 Response of water balance components to irrigation scenarios

Water balance components were simulated only for irrigation source from within the watershed. As expected, annual ground water contribution to the stream from the rice farms (GWQ) is highest under the CRC than under the SRI scenario for wet season (Fig. 21). During wet season, irrigation water lost from the farms as GWQ in CRC is about 144 mm (about 83%) higher than in SRI whereas there is not a noticeable difference in GWQ between the CRC and SRI during dry season. This lack of difference during the dry season can be explained by the fact that the water stress is the same between the CRC and SRI as shown in Table 13. The evapotranspiration from the rice farms (ET) during dry season appears to be about 20 mm higher (3 %) compared to wet season with no significant difference between CRC and SRI (Fig. 22).

Surface runoff contribution to the stream from the rice farms (SURQ) under the CRC is about 7 mm higher than under the SRI during wet season (Fig. 23). No noticeable difference in SURQ between
the CRC and SRI during dry season. Like the GWQ, the lack of difference in SURQ during dry season can be explained by the amount water stress during dry season as shown in Table 13. However, the presence of SURQ because of irrigation during wet season corroborates what was learned from interview during field visit to the UWAWAKUDA rice farms that there is normally a surface runoff returned to the river after irrigation water passing through farms. The outlet point of surface runoff to the river was also observed. What is lacking however, is the actual amount of water returning to the river for comparison because there was no gauging station at the outlet as observed during field visit.

Low SURQ, low GWQ and high ET during dry season strongly suggest that more irrigation water is needed during dry season while the opposite for wet season suggests that smaller amounts of irrigation water than the one currently applied may suffice.

5.2.3 Meaning and implications of the simulation results

The model results mean that significant water saving can be achieved without significant impact on rice yield by adopting the SRI under the conditions of the study area. The difference in the amount of irrigation water between the CRC and the SRI scenario, as simulated in this study, is 300 mm (Table 13). This is equivalent to about 44% saving in irrigation water. For the 1,700-ha rice farms used in the simulations, this translates to 5,100,000 m$^3$/year, equivalent to river discharge of 0.162 m$^3$/s. For the 17,027 ha of total rice area in the entire watershed, the saved amount would be 51,078,000 m$^3$/year, equivalent to river discharge of 1.6 m$^3$/s.

As per this model, the ground water delay (GW_DELAY) ranges between 0 and 229 days (Table 13). This implies that the excess irrigation water would be held in ground water storage for significant amount of time before being released back to the river, hence made unavailable for immediate use by downstream users or contributing to the recommended minimum river flow. The saved irrigation water could be used for domestic and industrial water supply but may also be used for sustainably increasing rice cultivation in the area as pointed out by Kahimba et al. (2014). The saved irrigation water, especially the surface flow component, would also mean reduced transport of nutrients and other pollutants from the farms to the river as found by Jung et al. (2014).
6.0 Conclusions and perspectives

6.1 Conclusions

Based on the model calibration, validation and scenario simulation results, the following conclusions can be drawn: firstly, the model performance can be concluded as satisfactory for the objectives of this study. This is because PBIAS has consistently been within the satisfactory range for both validation and calibration period, and that the study was intended for simulating average annual water balance (as opposed to day to day river flow dynamics) and annual crop yield. Additionally, NSE and $R^2$ values were all within the acceptable range for both calibration and validation period. Also, the fact that the model has been able to reflect reality in some respects e.g. results of scenarios in terms of rice yields and water saving agree with those from other published modelling and experimental studies, further increases confidence that the model was adequate for the intended application.

On the other hand, scenario simulations have shown that irrigation water can be reduced by about 44% without any significant decrease in rice yield. Interesting was the fact that the differences in rice yields between SRI and CRC were not significant regardless of wet or dry season. It can also be concluded that the availability of irrigation water during dry season is limited. Moreover, investigation into what happens to irrigation water has shown that avoiding excessive irrigation is especially important for minimizing GWQ and SURQ from the rice farms area. The former would render some water unavailable for immediate use (due to longer GW_DELAY) while SURQ from the farms would be a carrier of nutrients and other pollutants to the river.

6.2 Perspectives

Although the model and the results derived from it are associated with uncertainty, it offers an important insight into areas where improvements for future research and development are needed as outlined below:

- There is a need for watershed managers and other responsible stakeholders to step up efforts to improve both spatial and temporal data resolution (and quality assurance perhaps). This applies to both stream flow and weather data because missing data and sparse observation stations was one of the challenge in this study.
- All irrigation water users should be encouraged to install gauging stations at outlets of irrigation area so that measurements of how much water is returning to the stream as surface
runoff are made. This will be useful in more accurate quantification of water balance and studies of nutrients and other pollutants.

- Appropriate incentives may need to be designed by watershed managers to motivate the water users to install the gauging stations at the outlet of irrigation areas for measuring surface runoff returning to the stream.

- This model, and the methodology used here, can be a very useful learning tool and can be used by the QSWAT group at SUA in learning more about QSWAT and use it as an aid in training new QSWAT users.

- The model can also be a useful decision support tool for watershed managers at WRBWO, which will aid them in better understanding the hydrology of the Wami basin, and how various water users may influence this. In this case, they will need to refine the model further by increasing spatial-temporal resolution of observation data, increase details in land use and land cover map and details about ground water characteristics.

- The model would also be continuously upgraded when more capable newer versions of QSWAT are being released, as the model and the user interface is open source, and therefore available at no cost.

- Other researchers with interests like what was done in this Master’s Thesis could also benefit from the methodology applied in this study.
7.0 References


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