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Optimal Management Design of Irrigation and Related Resources: The Case of Central Rift Valley Region, Ethiopia

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Ph.D. Thesis

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Declaration

I declare that I have written my Ph.D. thesis aimed at "Optimal Management Design of Irrigation and Related Resources: The Case of Central Rift Valley Region, Ethiopia" independently under the guidance of my supervisor, **prof. Ing. Svatopluk Matula, CSc.** and co-supervisor **Ing. Kamila Báťková, MSc, Ph.D.** I have used the literature and other information sources that are cited in the work and listed in references attached at the end of this work. As the author of the thesis, I declare that I am responsible for its creation and did not trespass the copyright of the third parties.

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Abstract

The Central Rift Valley Basin (CRVB) in Ethiopia is an endo hydrogenic basin, where climate, land use and land cover (LULC) changes have affected the water resources. They are the critical challenges that need to be addressed in the region. This study explores the impacts of climate and LULC changes on the major components of the water balance such as surface runoff (Q), water yield (WY) and evapotranspiration (ET) in the CRVB. The methodology followed integrated modelling approaches to simulate the impacts of climate and LULC changes on the components of the water balance to search for possible optimum irrigation water management options. In the analyses, representative concentration pathways (RCP) data derived by the MIROC5-RCA4 ensemble climate models were downscaled from the regional climate models (RCM) under coordinated regional downscaling experiment (CORDEX) for Africa (CORDEX - AFR - 44) and applied. Both historical and projected data of climate emission scenarios of RCP2.6, RCP4.5 & RCP8.5 were downscaled, bias corrected and used. The data sets from the climate scenarios were applied to SWAT models to analyze the conditions of the components of the water balance in the near term (2031-2060) and in the long-term (2070-2099) periods in the region. The CRVB was divided into three sub-basins (Ketar, Meki, & Shalla) based on their river systems, and their water balance components were simulated with Arc-SWAT models, calibrated, and validated by SWATCUPs in SUFI-2 algorithm. The models were calibrated with monthly flows from 1990 to 2001 and validated with flows from 2004 to 2010. The baseline simulation data run from 1984 to 2010 separately for each of the sub-basin. The annual variations due to the climate change impacts are varying in the maximum ranges from -65.4 % to +85.8 % in Q, from -42.2 % to +23.9 % in WY and from -4.1 % to +17.3 % in ET when compared to the annual values of the baseline data simulation outputs in the sub-basins. Water management interventions that reflect the identified site-specific water balance sensitivities were proposed. Regarding LULC change, integrated

SWAT and Land Change Modeler (LCM) models were employed to evaluate the impacts of past and future LULC dynamics in the sub-basins. Past and future LULC analyses and predictions were done with LCM embedded in TerrSet 2020 software. LCM with a multi-layer perceptron (MLP) neural network for transition scenario analyses and a Markov chain method for predictions as well as SWAT model in fixing-changing methods for simulations were used to evaluate the conditions of hydrological processes for the LULC changes. LULC maps that represent past periods corresponding to the year 2003, 2008, 2013, 2020, and predicted maps of future periods for the years 2030, 2040 and 2050 were employed. The analyses resulted in an annual Q variation in the maximum ranges from -20.2 % to +32.3 %, WY from -10.9 % to +13.3 % and ET from -4.4 % to +14.4 % in the sub-basins due to the sole impacts of changes in LULC in comparison to the base LULC simulation outputs. The ranges of variation in the components of the water balance in each of the sub-basin due to the LULC changes were also huge and different. Based on the resulting simulation outputs, irrigation management options under climate and land use change dynamics were reviewed and proposed. The importance of water-irrigation-land use and climate change nexus synergies in relation to water requirement for agricultural purposes together with tradeoffs quantification for optimum or balanced resource use were also discussed. Further research on water-agriculture-land use and climate change nexus development approaches were recommended to manage their impacts on water resources and irrigation.

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Nomenclature

CA_MC - Cellular Automata Markov Chain

CMIP5 - Coupled Model Intercomparison Project - Five

CN - Curve number

CORDEX - Coordinated Regional Downscaling Experiment

CRVB - Central Rift Valley Basin

DEM - Digital Elevation Model

ET - Evapotranspiration

GCM - General Circulation Model

GIS - Geographic Information System

HRU - Hydraulic Response Unit

LAI - Leaf Area Index

LCM - Land Change Modeler

LULC - Land Use and Land Cover

MIROC - Model for Interdisciplinary Research on Climate

MoA - Ministry of Agriculture

MLP - Multi Layer Perceptron

MoWR - Ministry of Water Resources

MWIE - Ministry of Water, Irrigation and Energy

Mm^3 - Million-Cubic Meters

NMA - National Meteorological Agency

NSE - Nash Sutcliffe efficiency

OBANR - Oromia Bureau of Agriculture and Natural Resources

P - Precipitation

PBIAS- percentage of biasedness

Q - Surface Runoff

R^2- Coefficient of determination

RCA4 - the fourth Version of the Rossby Center Regional Atmospheric Climate Model

RCM - Regional Climate Model

RCP - Regional Concentration Pathways

SCS - Soil Conservation Service

SNNPR - Southern Nations, Nationalities and Peoples Region

SSI - Small Scale Irrigation

SUFI-2 - Sequential Uncertainty Fitting version 2

SWAT- Soil and Water Assessment Tool

SWATCUP - SWAT Calibration and Uncertainty Program

USDA - US Department of Agriculture

WB - Water Balance

WGEN - Weather Generator Software

WUA - Water User Association

WUE - Water Use Efficiency

WY - Water Yield

List of symbols

ET_o - Reference evapotranspiration

mm - Millimeter

MJ- Mega Joule

m - Meter

R_n - Net radiation at the crop surface

G - Soil heat flux density

°C - Degree Celsius

T - Mean daily air temperature at 2 m height

u_2 - Wind speed at 2 m height

kPa - Kilo Pascal

e_s - Saturation vapor pressure

e_a - Actual vapor pressure

Δ - Slope vapor pressure curve

r - Psychrometric constant

I - Inflow

O_i - monitored flow

S_i- simulated flow

S - Retention

ds - Change in storage

dt - Change in time

SW_t - Soil water content at a given time

R_{day} - Rainfall in that day

Q_{surf} - Surface runoff

E_a - Actual evapotranspiration

W_{seep} - Water seepage

Q_{gw} - Base flow

W_{yld} - Water yield

Q_{lat} - Lateral flow

T_{loss} - Transmission loss

t- t statistics

M- Sample mean

μ- population mean

S_m - Estimated standard error

SW_o - Initial moisture content

1. Introduction

Recurrent drought and climate variability are the major challenges of irrigation development in sub–Saharan Africa. In the African tropics, climate is characterized by large inter-annual to centennial variability in rainfall, river flow regimes and lake level that have enormous socio-economic impact (Legesse et al. 2003). Combined with population growth of the region, climate variability poses pressure on natural resources utilization. Climate change mainly affects the temporal and spatial hydrological cycle and its settings (Bai et al. 2019; Liu et al. 2019). Water cycle process which is the main source of fresh water is highly maneuvered by these climate change impacts (Dey & Mishra 2017). The impacts could be manifested in extreme drought, over flooding, unusual and untimely weather occurrences (Mancosu et al. 2015). Typically, climate change results in an increase in atmospheric temperature and modification of precipitation patterns (Liu et al. 2019). Among different components of water cycle in a watershed, streamflow is the most important part for water resources management and its variability affects the water use pattern in different sectors like agriculture, domestic water supply, industry, energy, and in navigation (Mancosu et al. 2015). Since water availability and accessibility are the most significant factors for crop production and other vital functions, addressing this issue is indispensable for areas affected by water scarcity. Water scarcity owing to recurrent drought and weather variability are the major challenges of irrigation development especially in sub–Saharan Africa (Awulachew et al. 2005).

In the African tropics, the climate is characterized by large spatial and temporal variability in rainfall and its consequent river flow regimes. As a result, the demand for food, energy and water is on the rise (Ofori et al. 2021). According to Ngigi (2009), agricultural productivity in sub-Saharan Africa is also low due to poor natural resource management and limited capacities to adapt to adverse weather, climate variability and extreme events. Since the livelihoods and wellbeing of many of the people in the region are directly dependent on the ecological character of the ecosystem, very careful considerations need to be given to determine how water in the basin should be managed and utilized. Some past studies indicated that the management of water resources at basin scale ought to be based on the climate and weather forecasts (Feleke 2015; Shumet & Mengistu 2016).

Smallholder agriculture is the major economic activity of Ethiopia particularly in the Central Rift Valley Basin (CRVB). It accounts to 47.7 % of the national gross domestic product and 85 % of the employment (The World Bank 2014) compared to the 13.3 % from industry and 39% from services. Population is growing at an alarming rate, 2.3 %, (Mekuria 2018) and as a result, irrigated agriculture is expected to expand in the area, increasing the demand for water in the basin. Thus, water resource conditions of the area should be monitored and managed accordingly (Pascual-Ferrer & Candela n.d.). This requires serious regular climate data analyses, simulations and forecasts to develop adaptation mechanisms based on site specific challenges and water conditions to optimize the water uses particularly irrigation and its water uses (Teshager et al. 2016).

A climate impact study can also provide a reliable basis for water resource planning (Mengistu et al. 2021). Nowadays, long-term water resource planning and studies need to take into consideration ongoing and future global climate changes in order to curb the uncertainties in the management of the water resources (Beyene et al. 2010). In such studies, the effects of climate change must be quantified with high spatial and temporal resolution at basin scale (Taye et al. 2018; Musie et al. 2020b; Worku et al. 2020; Pascual-Ferrer & Candela n.d.). Various climate models at regional scale and at global scale have been developed to address the impacts of possible future climate change in coarser resolution with different scenarios (Setegn et al. 2008; Hagemann et al. 2013; Gadissa et al. 2019a).

The models can be applied to analyze the impacts of changes in climate on water resources (Hagemann et al. 2013). These models investigate the degree to which observed changes in climate may affect the resources due to natural variability, human activity, or a combination of both (Desta & Lemma 2017). The results and projections produced by such models provide essential information for making decisions of local, regional and national importance on matters such as water resources management, agriculture, transportation, and urban planning (Liu et al. 2019). However, hydrological models need to be calibrated to site-specific conditions before they are used for climate change impact analyses (Beyene et al. 2010). Similarly, global circulation models (GCM) that predict long-term climate trends (rainfall, temperature, and humidity) are often unsuitable for regional scale studies because of their coarse grid-size resolution. It is therefore essential to downscale GCM data to the region-specific climate impact (Kotamarthi et al. 2021). The study presented here is therefore aimed at analyzing the impacts of climate change according to the RCM-RCP emission scenarios on the major water balance components of CRVB in Ethiopia, using the SWAT model, to find feasible sub-basin-wide water management practices and to optimize the use of scarce water resources.

In addition, ecosystem change such as land use change and its impacts on water resources must be monitored to manage the resources sustainably. In response to the high population density and poor capacity in managing water resources, better sustainable resource development and resilient economy to the extreme weather variables should be fetched and developed in integrated ways (Awulachew et al. 2005). The competing nature of people on resources i.e., the population growth and their impacts on resource use, the conflicting interest of resource uses, and its diminishing nature such as: soil fertility loss, land use change, rise of energy demands which in turn has degrading impacts on environment and extreme weather variabilities as well as climate change, has enhanced the need for irrigation expansion in the area. All ought to be managed together with other resources development approaches in synchrony. Therefore, it is crucial to use efficient and interlinked multi stage resource development, utilization and management approaches in synergy (Al-Saidi & Elagib 2017). Integrated resource management helps in sustaining irrigated agriculture for food security and preserving the associated natural environment (Cai et al. 2003).

However, most previous studies on climate change in Ethiopia have often been limited to assessing impacts on current agricultural systems without accounting for potential adaptation and management options that optimize the water balance based on climate and land use change forecasts at basin scale. The aim of this study is thus to analyze the impacts of climate and land use and land cover changes on water resources particularly on agricultural water at basin scale and to fetch for its optimum management options in the region. And to indicate the future climate trends and its mitigation and/or adaptation options while developing irrigated agriculture.

2. Hypotheses and objectives

2.1. Hypotheses

1. Climatic variabilities, existing land use and water management practices affect water resource potential use and its development in the CRVB.

2. Land use management can improve water resources potential and thus reduce risks during extreme weather variabilities.

2.2. Objectives

This study primarily focuses on analyses of optimal management of irrigation, water, and other related natural resources at the face of changing climate and land uses.

Specifically:

1. To simulate the impacts of climate change on the components of the water balance for irrigation development and to device agricultural water management strategies in the CRVB for the impacts.

2. To analyze the impacts of land use and land cover change simulations in affecting the water resources potential use in the CRVB and to propose optimum land use and water management options.

3. To review and recommend optimum irrigation water management options in the CRVB in nexus synergies of water, irrigation, land use and climate changes.

3. Literature review

3.1. Climate change and agricultural water management

Climate change is one of the most critical challenge that is highly expected to affect specifically the hydrological processes such as precipitation and evaporation (Bedeke 2022). This can have direct impact on stream flow, surface runoff and ground water recharge and thereby on water storage potential of reservoirs and aquifers. It also has great implications for hydrological cycle and for water resources planning. Climate change also has important implications for existing water resource as well as for future water resource planning and management (Tesfahunegn & Gebru 2020). With increase in temperature, climate change is accelerating the global hydrologic cycle (Reshmidevi et al. 2018). Climate change is also projected to cause changes in precipitation pattern, variation in the frequency and distribution of floods and droughts, and increase in evapotranspiration rate over different regions in the world (Reshmidevi et al. 2018). These changes are believed to affect agricultural water management at large. For instance, under the climate change in recent years, the imbalances between water supply and water demands have been increasing, which have given rise to great attention from both the relevant authorities and the public to water resources planning programs (Ficklin et al. 2009). Hence, urgent action is required for understanding and solving potential water resource problems for human's existence and well-being, especially, quantitative estimates of hydrological effects of climate change are essential (De Girolamo et al. 2017).

Thus, agricultural water management is one of the essential programs that need to be improved with climate conditions. Improving the management of agricultural water use is of utmost importance, as irrigation water uses account for 70 % of the global freshwater withdrawals, providing now about 40 % of the world’s food and expected to expand more extensively and intensely with human population growth and needs (Saghir 2014; “Farmer-led irrigation” n.d.). However, use of water for agricultural production in water scarce regions requires innovative and sustainable research and appropriate transfer of technologies (Pereira et al. 2002). The sustainable use and development of water resources in the era of climate change are thus a priority for agricultural water management in water scarce regions. In addition, irrigation and its water management innovations are very necessary as the agriculture sector is highly affected by water scarcity (Pereira et al. 2002).

Water scarce regions are characterized by imbalances between availability and demand, by degradation of surface and ground water qualities, by inter sectoral competition, and by inter-regional and international conflicts. Water scarcity occurs mainly as nature produced and man induced (Smit & Skinner 2002). Thus, policies and practices of irrigation water management under water scarcity must focus on specific objectives according to the case of the water scarcities. For instance, irrigation management must consider climate impact trends of the region on stream flows while planning irrigation development and its water uses. Adjusting irrigation water management to the water balance trends due to climate change is one of the adaptation strategies to curb the impacts. Adaptation in agriculture to climate change is also important for impact and vulnerability assessment and for the development of climate change policy (Ayenew 2007). Different scholars indicated various adaptation options of agricultural water management in water scarce regions due to the climate change. The four major categories of climate adaptation in agriculture that were recommended are as follows:

i) Technological developments
ii) Government programs and insurances
iii) Farm production practice improvement
iv) Farm financial management (Smit & Skinner 2002). Information provision is also indicated as the good simulator of the adaptive initiatives.

Agriculture is the topmost sector that may be affected by changes in climate as both crop production and livestock systems depend directly on climatic factors such as rainfall and temperature. The variabilities in these factors due to climate change significantly affect the crop water requirement, water availability and water quality (Cai et al. 2015). Climate change affects crop water requirement in a manner that its evapotranspiration is modified. Evapotranspiration (ET) is the measure of crop water requirements both in rainfed and in irrigated farms. An increase in temperature and sporadicity in rainfall will increase crop ET and as a result, crop failure due to water scarcity will occur. These will consequently impact productivity and global food security. Precipitation is the source of both green and blue water and its variability due to climate change will affect water in storage reservoirs, in lakes and in rivers. Climate change also damages the green water available in the plant root zone which is useful for plant transpirations. Irrigation water supply for crop production is thus affected at large due to the loss of these blue water sources. Irrigation water management planning should therefore be conducted insight to the climate change impact analyses and forecasts (Cai et al. 2003). Extreme events and climate change can damage the quality of blue water sources and makes it difficult to use directly for crop production. These hamper and retard the usable capacity of the source and makes irrigation and agricultural water management costly (Cai et al. 2015). Therefore, agricultural water management practices and their improvement must follow and consider the climate change impact analyses.

3.1.1. Climate change impacts and water resource management in the sub-Saharan Africa

Sub-Saharan Africa is the most vulnerable zone to the impacts of climate changes (Ayenew 2007; Bedeke 2022). In the region, the problem could be more pronounced because of rain-fed agriculture accounting for approximately 96 % of overall crop production. Rainfall usually affected by these plausible climate changes in the region (Getnet et al. 2014). Often, high temperature and the unpredictability of the rainfall leads to a natural disaster like droughts, heavy rainstorms and flooding in the region (Gurara et al. 2021). In sub-Saharan region, at the end of twenty-first century, the temperature is projected to rise roughly +2.0 to +4.5°C (Ofori et al. 2021; Gurara et al. 2021). The water resources potential is also under pressure because of the increasing population, new infrastructure, and irrigation projects (Serdeczny et al. 2017). The impact of climate change is not uniform in the region and East Africa is at higher risk of flooding, drought and concurrent health impacts (Getnet et al. 2014). Precipitation trend is not uniform across the region, with decreasing trend significantly in the horn of Africa (Conway et al. 2007). It shows an increasing trend in central and eastern Sahel, and a decreasing trend in western Sahel. Africa is widely held to be highly vulnerable to future climate change and Ethiopia is often cited as one of the most extreme examples (Conway & Schipper 2011).

Development of adaptation strategies to deal with potential impacts of climate change on hydrological systems is a critical challenge for water resources management in the sub-Saharan region. It is also tedious and complex to understand the climate change and hydrologic phenomenon at different spatial and temporal scales (Yira et al. 2017). Besides, water scarcity is becoming an increasing problem world-wide, especially in sub-Saharan Africa, due to rapid increases in population, urbanization and increasing water demands by industry and for food production (Pereira et al. 2002). Human influences such as deforestation and degradation are also exacerbating these problems in the region.

A study conducted by Serdeczny and his co-authors indicated that climate change in the sub region is also characterized by increasing warming trends of heat, increase in the inland aridity and in frequent occurrence of heat waves and drought (Serdeczny et al. 2017). Increase in infectious disease and under nutrition were more prevalent in the region due to climate change scenarios than the without scenarios (Ibid). As a result, human migration to urban areas which causes serious challenges not less than those problems at their original homes in the rural areas were observed and rise in food price is common. Impacts across sectors are also amplified climate being the root cause. Regional climate pattern indicated that temperature in the low- emission scenario, RCP 2.6, increase until 2050 at about 1.5°C and above. In the high emission scenario, RCP8.5, warming continues to end of the century and monthly temperature rise may reach up to 5°C all over the sub Saharan Africa (Serdeczny et al. 2017). Changes in precipitation in the region follows a dipole pattern of wetting and drying in both high and low emission scenarios and its variation could reach from 10-30 % in terms of percentage either in reduction or increment (Hendrix & Glaser 2007).

In general, understanding and addressing the impacts of climate change are important. Climate changes must be addressed based on two basic premises: mitigation – reducing the cause of anthropogenic activities on the natural environment and, adaptation – preparing for the effects of a changed environment on human beings. Adaptation can be either reactive or anticipatory. It is more than just policy implementation or technology application (Ngigi 2009). It involves multi-stage iterative process. These are: information development and awareness raising, planning and design, implementations, monitoring and evaluations. In understanding, the root causes should be assessed and known. The causes of climate changes are inherently linked to global warming which is the anthropogenic activities directly linked with rapid exponential population increases in most African nations (Pereira et al. 2002). Ethiopia is among the most vulnerable countries in sub-Saharan Africa due to its great reliance on climate sensitive sectors, particularly rain dependent agriculture (Conway & Schipper 2011; Kassie et al. 2015). Various global and regional studies warn that progressive climate change is expected to negatively affect crop productivity in most parts of the world and particularly in Ethiopia (Teklay et al. 2021).

In depth understanding on the trends of changes in climate are very important. River basin rainfall series and extensive river flow records are used to characterize and improve understanding of spatial and temporal variability. Rainfall and river flows in Africa display high level of variability across a range of spatial and temporal scales, with important consequences for the management of water resource systems (Conway et al. 2007). Throughout the continent, the variability brings significant implications for society and causes extensive suffering and damage to the economy. These variabilities manifested as prolonged low flows of rivers, and as multi-decadal anomalies of river flows. These water resource variabilities also pose challenges on lakes water level, on fisheries, in reservoir management and in irrigation management (Ayenew 2007; Conway et al. 2009). Managing these variabilities accordingly is therefore important to adapt the impacts.

3.1.2. Impacts of climate change in the CRVB, Ethiopia

In CRVB, there are high levels of rainfall variability, water scarcity and weather variability, thus, it is a place where water resources planning and management is greatly challenged by the impacts of climate change (Molla 2014). For example, an increase in temperature and variability in rainfall affected the seasonal and total water supply and led to the occurrence of extreme hydrological events (Molla 2014). Increase in ET has taken huge volume of water from the lakes (Ibid). A study also indicated that increased evapotranspiration consumed 62 and 145 Mm^3 of additional water from lakes and land surface, respectively, during 1990 – 2007 periods (Getnet et al. 2014). Significant reduction in lakes water level due to over exploitation are also common in the sub region (Ayenew 2007; Gurara et al. 2021).

Significant increase in surface runoff and ET up to more than 100 % for an increase in temperature by a less than 1^oC have also been observed (Abdi & Ayenew 2022). Similarly, climate change has brought significant impacts on water resources in the region; agricultural operations such as crop production, irrigation and cattle breeding as well as water supplies were affected (Uniyal et al. 2015; Shumet & Mengistu 2016; Worqlul et al. 2019; Musie et al. 2021). It is therefore essential to know the trends of climate change over a long period of time to manage possible extreme hydrological events, either droughts or flooding, in the region.

Various studies have been carried out for analyzing the water resources of the CRVB in an attempt to evaluate and describe the extent and the impacts of climate change on existing water resources (Feleke 2015; Gadissa et al. 2018; Getnet et al. 2014; Legesse et al. 2003; Muluneh et al. 2015; Tekle 2015). However, only a few of these studies have been aimed at analyzing the impacts of climate change based on various Regional Concentration Pathways (RCP) simulations in different emission scenarios to evaluate the conditions of the components of the water balance in the sub-basins. For example, in Ethiopia, Legesse et al. (2003), used the Precipitation-Runoff Modelling System (PRMS) to simulate runoff, and a 30 % decrease in runoff in response to a 10 % decrease in the amount of precipitation was predicted (Legesse et al. 2003; Jansen et al. 2007). A 1.5°C increase in temperature resulted in a 15 % decrease in runoff. Similarly, it was indicated that a higher temperature leads to an increase in evaporation rates, to reductions in stream flow, and to an increase in the frequency of droughts (Tekle 2015).

In addition, a vast number of studies have been conducted to analyze the impacts of climate change on crop productions (Legesse et al. 2010; Molla 2014; Kassie et al. 2015; Shumet & Mengistu 2016; Asefa & Temesgen 2021). On those studies, crop failure due to water scarcity, yield reduction and food insecurity challenges were reported due to the impacts. However, very little consideration has been given to the potential impact of climate change on the current and future water balance components in the region. The link between climate change and management or adaptation methods were also not well established. That is why, the climate impact analyses on surface components of the water balance of the region and agricultural water management options were sought in this study.

3.2. Land use and land cover changes and the water balance

Availability of water in a region is highly dependent on rainfall and its distribution over the areas. The water from the rainfall over an area is again distributed to various hydrologic components of lateral flow, surface runoff, evapotranspiration, and others. Land use and land cover and its changes can affect and modify these distributions and the quantity of these water cycle components (Kundu et al. 2017). Water cycle, land management, and environmental sustainability are highly interlinked (Kuma et al. 2021). Thus, land use and land cover management will have an impact on water availability either positively or the other way round.

Availability of agricultural land is an important determinant factor for food production. However, the change of agricultural land uses will be followed by the change in agricultural water management through the conversion of current rainfed lands to irrigated lands and vice versa. This agricultural land availability is subject to climatic change because the arability of land depends on many climate parameters such as temperature, precipitation, and so on. Specifically, soil temperature regime and air humidity are major determinants of agricultural land suitability, which are directly affected by climate change. Increase in soil temperature in temperate regions would generally benefit local agriculture, while excessively high soil temperatures in tropical areas are harmful to crops. Most of the arable land in sub-Saharan countries are affected by soil temperature and the yield outputs per unit area are smaller when compared to temperate regions due to these soil factors (Cai et al. 2015).

Crop land area in the sub-Saharan region may require more irrigation to maintain reasonable production. Adaptation measures such as rainfall harvesting, and water storage may help mitigate the negative impacts of climate change on land arability. Changes in agriculture management, such as adjusting crop type, growth season, and planting location, are also potential adaptation measures recommended (Cai et al. 2015; Belay et al. 2017).

Therefore, sustainable land and water management practices are vital for sustaining agricultural productivity and regional development (Khan & Hanjra 2008). Improving land and water management in agriculture and the livelihoods of the regional communities requires mitigating or preventing land degradation. Unsustainable land and water management practices can compromise the capacity of the ecosystems to provide livelihood and support services to mankind (Ayenew 2007; Khan & Hanjra 2008). Land cover plays a significant role in influencing the water and energy balance at the land surface via its effect on transpiration, interception, and evaporation from canopy leaves. Changes in vegetation cover can change surface roughness and Leaf Area Index (LAI), thus influencing the surface energy balance and evapotranspiration (ET). These influences may significantly affect the timing and magnitude of evaporative losses to the atmosphere and the amount of water yield that governs soil moisture content, runoff and baseflow patterns of regional hydrologic responses (Mao & Cherkauer 2009).

The management of a watershed is thus playing a major role in ensuring water resource availabilities. As the rapid development in various sectors leads to increase in water demands, optimum utilization of water resources is needed in the sustainable use of the resources or the need for integrated water resources management is vital. These integrated management involves land use and land cover management in line with water resource management. In the sub Saharan region, human activities especially agricultural land expansion at the expense of forest cover have been the primary reason for land use change (Asefa & Temesgen 2021; Regasa et al. 2021). Therefore, the consequence of these agricultural land use change is resulting in changes in flow characteristics which should be managed accordingly (Mao & Cherkauer 2009).

3.2.1. Conditions of land use and land cover in CRVB.

Several studies that have been conducted in many parts of Ethiopian rift valley region and beyond revealed that agricultural land had been expanded at the expense of natural vegetation, forest and shrubs as well as grass lands (Legesse et al. 2003; Tekleab and Kassew 2019; Belihu et al. 2020; Wolde et al. 2021; Sulamo et al. 2021; Yifru et al. 2021; Anand et al. 2018; Rajaei et al. 2021; Hu et al. 2021; Regasa et al. 2021). The studies further revealed that water resources in the rift valley lakes are highly sensitive to land use and land cover changes. According to the studies conducted, significant changes have been observed in the hydrology of the Rift Valley lakes in Ethiopia over the past four decades. Lakes, e.g. Lake Abiyata has declined in size over the past years (Ayenew 2007). The volume of Lake Ziway has also decreased due to over exploitation and, reduced recharging due to reduced stream flows to the lake because of changes in land use in the upper catchments (Desta et al. 2015). Furthermore, development of large-scale irrigation, and industrial abstraction from the Central Rift Valley (CRV) lakes and the intensive agricultural and poor water management practices have modified the hydrology of most lakes in the region (Seyoum et al. 2015). Moreover, in the area, increase in small and large-scale farming, settlements, and mixed cultivation/acacia while a decrease in water bodies, forest, and open woodlands also pose remarkable challenge to the water balance conditions of the region (Elias et al. 2019).

Studies also revealed that extensive land degradations and soil fertility loss due to the prominent land use change in the sub region has affected the water balance environment of the areas (Desta & Fetene 2020). However, little considerations were given to the interaction of water balance components in the catchments to LULC changes. Thus, this study tried to simulate the impacts of LULC change on hydrologic components of the sub-basins in addition to the analyses of climate change impacts on the major components of the water balance.

3.3. Irrigation practices in Ethiopia, particularly in CRVB

Irrigation can be defined as an artificial application of water to soil for the purpose of supplying the moisture essential in the plant root-zone to prevent stress that may cause reduced yield and/or poor quality of harvest of crops. It is a complex mixture of technical, institutional, economic, social and environment processes (Burton 2010). Irrigation has been practiced in Ethiopia since the ancient times though the exact time is not clearly indicated. Modern irrigation started and expanded after 1960’s with the intension of producing industrial crops such as sugar cane and cotton for the sugar and textile industries built in the country (Awulachew et al. 2007). Different scholars also agree that traditional irrigation was practiced in Ethiopia many centuries back to supplement their small farms (Awulachew et al. 2005; Awulachew et al. 2007; Bacha et al. 2011). These irrigation practices have not matched the available potential and capacity in terms of productivity. Moreover, in Ethiopian agriculture, smallholder farmers' economy can be significantly improved through irrigation. Irrigation is also the key to sustainable and reliable agricultural development. To ensure food security at household level, small, medium, and large-scale irrigation infrastructure development is very crucial for fast growing Ethiopian population (Awulachew 2019).

Irrigation is assumed to be one of the basic strategies to alleviate poverty by transforming the rain dependent agriculture to fully irrigated and supplementary agriculture in the country, ensuring food security. Nowadays, due to the efforts from different stake holders and government attentions, irrigation infrastructure development is improving year after year in the country from small to large scale irrigation systems (Belay & Bewket 2013). Scholars, as stated in the document of Ministry of Finance and Economic Development of Ethiopia, (2010), agreed that irrigation is useful to mitigate impact of climate change, to address the main challenge caused by food insecurity and water scarcity, and to stimulate the economy. Thus, promotion of small-scale irrigation (SSI) is identified as one of the priority policies for Ethiopia. Belay & Bewket (2013) also explained that irrigation water is critical to poverty alleviation through increased production in rural areas to improve food security and rural livelihoods. Besides its importance in improving livelihoods, irrigation development in Ethiopia is at its low stage performance in infrastructural coverage, operation, and management (Belay & Bewket 2013; Awulachew 2019). Performance of irrigation schemes, modern as well as traditional, is influenced by a host of biophysical and social factors such as relief, climate, soil, water, cultures, institutions, and laws (Habtu & Yoshinobu 2006). Poor irrigation water management and its related consequences are also the main cause for the low irrigation performance in the country (Awulachew & Ayana 2011). Ethiopia has great opportunity in water-led development, but it needs to address critical challenges in the planning, design, delivery, and maintenance of its irrigation systems if it is to attain its full potential (Awulachew 2019).

In CRVB, irrigation farming is practiced both at large scale commercial level and in many medium scale to small scale levels for crops, vegetable, and fruit productions. Smallholder irrigated vegetable production in the Central Rift Valley region of Ethiopia is important in ensuring a year-round availability of fresh vegetables in the capital market (Etissa et al. 2014). However, these irrigation practices are highly affected by water scarcity as well as water quality damages due to climate change, urbanization, industrial effluent, and other anthropogenic activities such as land use and land cover changes, damage to the soil and deforestations (Desta & Fetene 2020; Wolde et al. 2021).

3.3.1. Irrigation water management practices and its challenges in Ethiopia

Despite the potential benefits of irrigation are great, the actual achievement in many irrigated areas of the country is substantially less than the potential due to poor water management and its consequent effects and related problems (Yohannes et al. 2017; Awulachew 2019). In Ethiopia, despite significant efforts by the government and other stakeholders, water management in irrigated areas is hampered by constraints in policy, institutions, technologies, capacity, infrastructure, and markets (Awulachew 2019). Even if there are increasing investments in small-scale irrigation, the poor performance of current water management practices and its institutional arrangements in the country seem to jeopardize the sustainability of the irrigation schemes (Amede 2015). Poor and very traditional water management is highly reducing the performances of modern small-scale irrigation schemes productivity in the country (Belay et al. 2017). If the country is to achieve its stated aims of food self-sufficiency and food security, substantial improvements in water management are needed at farm and watershed scales (Kassie et al. 2015). As the country varies in its socio cultural, hydrological, soil and in climatological settings, incentivizing and investing in irrigated farm water management equally with proportionate infrastructural development is crucial in improving and sustaining irrigation performance according to these variabilities and socio-cultural settings (Derib et al. 2011; Amede 2015). Awulachew and his co-authors proposed a collective action to improve irrigation performance by all stake holders; government agents, donors, and non-government organizations', in sustained and planned ways (Awulachew & Ayana 2011; Awulachew 2019). Some studies also indicate that the water management problems emanate from economic, social, and environmental challenges and thus integrated catchment-based management is suggested to succeed in irrigation water management effectiveness at farm level (Batchelor 1999).

In the country, economic inefficiencies of the farmers enhance the failure of irrigation performance and its endurances, inhibiting continuous investment in inputs and in its operation to milk out the full potential (Awulachew & Ayana 2011). To foster the intended development and food self-sufficiency via irrigation, incentivizing the farmers in system operation, water management, scheme maintenance, and in agronomic services are very crucial. Institutionalizing the practices with all legal and administrative tools, i.e., devising operation and maintenance, water management, and establishing market linkages for the inputs and products with full participation of the user community in organized ways according to site specific conditions could be one of the affirmative incentives to improve the performance of irrigation schemes (Meinzen-Dick 2007).

According to different reports and research findings, the major reasons affecting the performance and sustainability of irrigation schemes are poor water management, excessive siltation, poor agronomic support, and the failure of local institutions to sustainably manage the schemes (Etissa et al. 2014; Yohannes et al. 2017). The Ministry of Agriculture (MoA) emphasizes that the capacity to invest in quality and improved water application system to improve irrigation water management as a whole need to be improved equally with irrigation system development expanding these days in the country (Awulachew & Ayana 2011). For instance, the improvement of irrigation water application in large public irrigation, such as Wonji and Finca'a, schemes in producing industrial crops such as sugar cane from furrows to sprinkler has tremendously improved the farm performance, productivity, reduced water loses and protect soil degradations from salinity and logging from excessive seepages (Awulachew & Ayana 2011). Poor irrigation water management combined with traditional way of cropping have also resulted in water and yield loss, and undesirable environmental impacts (Agide et al. 2016).

Environmental degradation in semi-arid regions of the country where irrigation is highly operated, siltation or sedimentation of irrigation structures is highly intensive and makes irrigation water management difficult and costly (Derib et al. 2011; Belay & Bewket 2013). These huge sedimentation problems in most irrigation schemes are the reflection of poor considerations for watershed management while developing irrigation schemes which is the main challenge for most irrigation schemes failure and low performances (Batchelor 1999). An assessment indicated that the huge sedimentation in the river system due to unprotected catchment and severe erosion have abandoned some schemes and makes others to perform below the planned command areas in

Ethiopia (Habtu & Yoshinobu 2006; Yohannes et al. 2017). Siltation of the irrigation canals and other on and off farm infrastructures are the biggest obstacle for efficient water abstraction, distribution, and applications (Yohannes et al., 2017). Poor water management also deteriorates the soil profile in the farms and favors water losses (Ulsido et al. 2013). Usually, extra water was applied to most of the farms beyond the required amount but the cropping intensity, the output per water supplied or per unit area is very low and sometimes less than the rain fed farming, indicating that irrigation water management and irrigation agronomic support should be given due attention (Awulachew et al. 2007). According to the World Bank report, (2007), Ethiopian government has also given due attention to address water scarcity for agricultural production via irrigation from water harvesting structures but the recent issues lie in the sustainability of the systems (Ayenew 2007).

However, to feed the over increasing population of the country, irrigation area expansion coupled with production improvement per plot was forecasted as indicated in Table 1 based on the national population consensus of 1984: what irrigation coverage in hectare (ha) and production tone per hectare (t/ha) or million tons per hectare (Mt/ha) should look like up to the year 2020 to cover up the country's need (Awulachew et al. 2007). Nevertheless, in recent years there have been improvements in irrigation coverage, (Awulachew 2019), but the expected production output per unit area or per unit of water supplied still needs to improve. Moreover, the demand for more water or water scarcity has been aggravated by expanding agricultural needs due to population growth and climatic variabilities (Ayenew 2007; Yohannes et al. 2017), however, land degradation, poor water management practices, and limited institutional and household capacities to store and efficiently utilize available water resources deepen the challenges (Amede 2015; Gebul 2021). Thus, integrated irrigation water management, watershed, and institutional development approach to improve irrigation performances, and sustainability are to be implemented equally with its infrastructural developments.

Table 1. Forecasted population, food crop production & irrigation land in Ethiopia

Year	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Population ('thousands)	53,277	60,965	70,297	82,689	96,806	113,234
Annual Per Capita Food Consumption (kg)	150	160	170	180	190	200

Total Requirement of Cereals in million tones (Mt)	7.99	9.7544	11.95	14.88	18.39	22.64
Production from rain fed Cultivation (Mt)	7.491	7.99	8.49	8.99	9.99	10.99
Balance Production from irrigated agriculture (Mt)	0.50	1.7644	3.46	5.89	8.40	11.65
Production rate for irrigated Agriculture (t/ha)	6.5	7	7.25	7.5	7.75	8
Required area under irrigated Agriculture (Mha)	0.07	0.25	0.47	0.78	1.08	1.45

Source: Awulachew et al. (2007)

3.4. Factors influencing irrigation water management

3.4.1. Lack of irrigation farm mechanization

Land leveling and preparations are among the major challenges that affected on-farm water applications in irrigated fields (Jat et al. 2004; 2015). As most of the irrigation methods in Ethiopia is surface irrigation, (Yohannes et al. 2017), land grading and leveling is highly required for uniform and efficient water application. Surface irrigation methods depend on gravity and slope that permits water flow in a field. In Ethiopia, irrigation water is applied to the farm mostly through irrigation furrows (Eshete et al. 2020). The furrows are usually made using the traditional plough pulled by animals, which has shallow depth and narrow width (Belay & Bewket 2013). The irrigation water in most cases overtops and destroys these furrows resulting in flooding. Flooding of farms due to furrow breaching is also the main reason for water loses in most water scarce irrigated farm areas and this brings undesired environmental impacts (Ulsido et al. 2013; Yohannes et al. 2017). Many studies indicated that the furrows are highly affected by the poor flow control, poor land levelling or grading practices and lack of appropriate drainage systems (Jat et al. 2004; 2015; Awulachew 2019). The traditional oxen and manpower farming makes the irrigated land preparations very tedious and thus affects irrigation and its water management. It is known that irrigation is one of the labor-intensive rural production system but the traditional farming practices in the country exaggerate the challenge (Eshete et al. 2020).

In general, Jat and his co-authors indicated in their studies based in India that declining irrigation water availability and crop productivity and increasing food demand necessitate quick adoption of modern scientific technologies for efficient water management (Jat et al. 2015). In their studies due to lack of land leveling, significant amounts (10-25%) of irrigation water is lost during application at the farm due to poor management and uneven fields. Even though Ethiopia is well endowed at least in part with a fertile soil, abundant water resources and good climatic conditions (Awulachew 2019), quite recently, the problem of low production can largely be related to low technical efficiency from using traditional and archaic production and operation implements (Amare & Endalew 2016). Improved seed and fertilizer inputs have been tremendously affected by land preparation and these farm production outputs from the improved seeds and fertilizer application are still far below outputs from sub-Saharan countries of similar nature and applications. This is largely due to poor mechanized farm operations the country is experiencing (Amare & Endalew 2016). Irrigated land leveling has many benefits; it is known to enhance water-use efficiency and consequently water productivity, helps even distribution of soluble salts in salt-affected soils, increases cultivable land area up to 3-5 %, improves crop establishment, reduces weed intensity and results in saving in irrigation water (Jat et al. 2004). Therefore, agricultural mechanization works on irrigated farms should get due attention for the performance and sustainability of irrigation in the country at all scales be improved. Inappropriate irrigation methods due to undulated farms are among the major causes for poor irrigation water management of SSI in Ethiopia. Thus, irrigation system development alone is not the mere solution to production improvement unless coupled with necessary farming mechanization, improved water application methods and managing capacity improvements. Irrigation together with mechanization of agriculture, use of improved seeds, and use of inputs such as fertilizers and pesticides in the 1960s significantly contributed to the Green Revolution in Asia (Hazell 2009). This is the adequate evidence for developing sub-Saharan countries including Ethiopia to replicate similar conditions that led to surplus production in Asia over the last 50 years.

3.4.2. Evaporation loses

Global warming due to rising concentrations of anthropogenic greenhouse gases enhances the evaporation loss which consequently increases the frequency of mild to severe drought events in the sub-tropical region. This phenomenon has brought significant impacts on irrigation water use effectiveness between irrigation intervals (Gizaw & Gan 2017). On-farm water management practices of surface irrigation in water scarce regions are thus highly influenced by evaporation losses. As a result, surface irrigated farms fall short of the potential levels. In the savannah regions including vast part of Ethiopia, rainfall generates only a minimal amount of blue water, and the largest part of rainfall is lost through evaporation (Conway & Schipper 2011). Climate change is projected to cause changes in precipitation patterns, variation in the frequency and distribution of floods and increase in evapotranspiration rate over different regions in the world. As such, the increasing need for irrigation water and scarcity of water is a rising issue (Reshmidevi et al. 2018). This suggests that better management of 'green water' can significantly compensate for lack of blue water (Asmamaw 2017). On farm water management or application technology improvement and soil management is the decisive way out of it (Pereira et al. 2002). The main pathways for enhancing water use efficiency (WUE) in irrigated agriculture are to increase the output per unit of water (engineering and agronomic management aspects), reduce losses of water to unusable sinks and its escape via evaporation before used by the plants, reduce water degradation (environmental aspects), and reallocate water to higher priority uses (societal aspects) (Asmamaw 2017; Gizaw & Gan 2017; Pereira et al. 2002).

Vast majority of the Ethiopian semi-arid and sub humid regions where crop production is highly carried out are affected by serious moisture stresses (Gizaw & Gan 2017). On average, the annual rainfall in this region is 700mm which is supposed to be enough for crop production but crop failure due to moisture stress is very common (Ayenew 2007). Besides, food insecurities are mostly prevailing and frequent famine is occurring in the regions. Asmamaw et al. (2017), with many more scholars, indicated in their findings that the main reason for moisture stress is soil evaporation from both irrigated and rain-fed farms before used by the plants. Soil evaporation represents a major non-productive loss of water from the soil–plant system and reduces water use efficiency (Gizaw & Gan 2017). Irrigation has got better attention than ever before in Ethiopia, but the irrigated farm production is still very low compared to the relative expected output even when more than the required water is applied to the farms (Awulachew & Ayana 2011; Haile & Kasa 2015; Asmamaw 2017). Farmers in these areas constantly face the problem of crop failure due to water scarcity although more than required gross quantity of water is supplied for the irrigated farms (Haile & Kasa 2015). Soil evaporation accounts for about 60-70 % of the annual rainfall in semi-arid regions in the country (Asmamaw 2017). Surface runoff and soil surface evaporation are the major water losses in the country. Thus, to improve the water productivity of both rain-fed and irrigated farms, proper water application and integrated in-situ soil and water management practices on farm fields are necessary.

3.4.3. Environmental impacts; water logging and salinity

Ethiopia's irrigation production has been affected by heavy waterlogging and salinity problems and it lowers yields than the potential it can offer (Gebrehiwot 2018). The major cause of waterlogging is lack of drainage systems in the Vertisols-dominated highland areas of the country while salinity is a common phenomenon in the large and medium scale irrigation schemes located in the lowlands. Irrigation water allocation, and management problems are also the major causes for water logging and salinization of most irrigation farms (Belay & Bewket 2013; Haile & Kasa 2015; Yohannes et al. 2017). On farm water application practices, which is mostly surface irrigation on unleveled land systems in long furrows also resulted in water logging and salinization in heavy clay soil types.

As indicated in the studies conducted by Cai et al. (2003) the United Nations Food and Agriculture Organization (FAO) in its 1996 report estimates that about 60 – 80 million hectares in the world are affected by waterlogging and salinity. They also reported that salinity and logging of the soil have impacted not only agricultural production but also human health. Hence, irrigation water management should address both agricultural production improvement to achieve food security and environmental protections to safeguard natural and human life (Cai et al. 2003). In Ethiopia, irrigation has been practiced at different farm levels for a long time, however, there is no efficient and well managed irrigation water management practice, as indicated in (Ulsido et al. 2013), which directly or indirectly does not affect the environment in the area. Environmental impact refers to any change in the environment or in its components that may affect human health or safety, flora, fauna, soil, air, water, climate, natural or cultural heritage, and other physical structures, social, economic, or cultural conditions (Ulsido et al. 2013). As indicated in their studies, even though there are production improvements via irrigation as conducted on four irrigation schemes in the central and southern regions, in the rift valley basins of the country, environmental impacts such as soil erosion, aquatic weeds infestation, sedimentation, infrastructural deterioration, unjust water distribution, are highly prevailing in those regions (Ulsido et al. 2013). This observation has been found in northeastern region of Ethiopia as well (Yohannes et al. 2017). Belay & Bewuket, (2013) discussed the high severity of environmental degradation due to ill irrigation practices in northwestern parts of the country by taking some irrigation schemes as case indicators in their studies. They concluded that poor irrigation management, soil erosion, leaching and malaria infestation at some low land waterlogged canals and sedimentations were some severe environmental challenges (Belay & Bewket 2013). These environmental challenges in any forms reduce the performance and deter the sustainability of irrigation schemes in most parts of the region (Awulachew and Ayana 2011; Gebrehiwot 2018; Ulsido et al. 2013). Therefore, proper water management (right allocation, efficient application, and effective use), environmental protection (soil and water conservation in the upper catchments) and coordinated on/off farm drain ditch maintenance, regular upgrading of irrigation and drainage systems are crucial in sustaining the performance of irrigation and in keeping the environment safe.

3.4.4 Water shortage or scarcity

Shortage of water is also one of the major factors affecting production and productivity of the irrigated crops in most irrigation schemes in the country (Belay & Bewket 2013; Yohannes et al. 2017). Policies and practices of irrigation water management under water scarcity must focus on specific objectives according to the causes of water scarcity. Pereira (2002) in his work explained that combating water shortage requires the following:

- Re-establishing the environmental balance in the use of the natural resources
- Restoring the soil quality
- Strengthening erosion control and soil conservation
- Combating soil and water salinization
- Controlling groundwater withdrawals and favoring aquifers recharge
- Minimizing water wastes
- Managing the water quality

Water scarcity in Ethiopia is aggravated by climate change, poor water management, and environmental degradations. Climate change has affected the physical water scarcity on a temporal and spatial basis. The poor and vulnerable populations of sub-Saharan Africa including Ethiopia will likely face the greatest risk, due to the low adaptation capacity to climate shocks according to IPPC 2007 analysis report (“Climate Change 2007” n.d.). Water scarcity from poor water management problems mainly emanates from economic water scarcity which is the inability of the country to develop enough and quality infrastructures such as irrigation facilities, storage ponds and dams to store, to divert, to convey or to distribute and transfer water resources to useable places timely and lack of strong soil and water conservation practices in the upper basins of irrigation schemes (Yohannes et al. 2017). The physical water scarcities in the region which are also the major challenge for irrigation water management during peak irrigation demands can be managed by improving the storage capacity of the country for excess water in the rainy seasons. Thus, economic constraints can be improved by implementing the necessary physical structures across the country. Physical scarcity can be mitigated via water saving and management such as efficient and effective water uses.

3.4.5. Engineering design and implementation constraint

Several authors indicated in their studies that at least 50 % of irrigation schemes in Ethiopia failed to give the intended returns largely due to design failures, thereby reducing the potential economic returns and negatively affecting farmers' livelihoods (Etissa et al. 2014; Haile & Kasa 2015; Awulachew 2019). Improper and dysfunctionality of most of the irrigation infrastructures as studies indicated are emerged from poor design considerations for proper location, dimension, operation, and maintenance easiness. The quality design selection in most schemes was misguided by the inherent costs that it incurs to implement. Though it is very meaningful for a developing country like Ethiopia to be economical while designing and implementing irrigation infrastructures, compromising the functional design quality of infrastructures is more uneconomical as some of the damages that are associated with poor quality design are irreversible. For instance, the salinity and logging problems of irrigated farms that are created due to poor design coupled with poor management capacity have led to abandoned irrigation farms in the country (Awulachew 2019). Poor design of irrigation water distribution methods has also degraded soil fertilities (Haile & Kasa 2015). Proper technical design and management improves the environment, as a result, reduces the salt and nutrient leaching from irrigated fields (Amede 2015). The optimal design and management of irrigation systems at farm level should therefore focus on the importance of a rational use of water, for economic development of agriculture and for its environmental sustainability. To ensure sustainable irrigation system design, it is critical to maximize the participation of farmers in all stages of the design process. This is important in the selection of the crop to be grown, type of system to use, layout of plots etc. Tuning the design to their social, cultural and environmental designing will fit their operation/maintenance capacities and interests (Hagos et al. 2009; Holzapfel et al. 2009). Participatory design also ensures that the designs are based on informed decision-making use of valuable local information especially as many designs in sub Saharan Africa are often carried out with limited reliable official data (Holzapfel et al. 2009). These will reduce the design and operation costs. Therefore, the technical design capacity gap that are also misguided by wrong perception of investment and operation costs must be averted to adopt efficient irrigation technologies while designing new systems and while upgrading the existing traditional schemes. Efficiently and effectively designed irrigation systems will ease its water management and perhaps its sustainability in addition to coping climate change impacts.

3.4.6. Institutional problems

Irrigation is usually considered as a unit of many perspectives, hydrologic entities, engineering networks, or as farming systems. A study also recommends seeing irrigation as organizational entities in which individual member constitutes a pattern and set of ideas to rules of actions and conditions of modifications for changes to be encountered (Coward 1980). These entities are interdependent and require appropriate institutions in aligning them together as one unit. For example, social and institutional factors such as land tenure, credit, water-sharing, arrangements in conflict management and legal institutions have influenced irrigation performances in the country (Belay & Bewket 2013). The study also indicated that the most important reasons for the failure of schemes in Ethiopia are lack of capacity for design, fail to regularly maintain the schemes and weak institutional arrangements. Organizational arrangement without the proper institution is the major cause for many water users associations (WUA) unsuccessful stories prevailing in the country (Awulachew 2019). Community participation, defined as engaging users of schemes in the decision-making processes from the planning to implementation of irrigation projects, is critical for the sustainability of irrigation schemes (Meinzen-Dick 2007). Irrigation development by its nature interlinks water, land, crop, and human interventions and must be managed in well-established institutionalized ways. Community self-initiated participation in framing WUA and its bylaws without enforcing pre-defined bylaws were relatively more effective than those institutions established by third parties usually in top-down approach from government sectors (Belay & Bewket 2013). In Ethiopia, a study indicated that traditional irrigation schemes that are managed by the community themselves are more sustainable and effective than modern schemes implemented by government bodies in same localities (Haile & Kasa, 2015). Though institutionalizing irrigation management is very crucial, understanding the clear site-specific driving forces, culture of farming and awareness of the user community is also important (Batchelor 1999). In institutional arrangements, where farmers no longer play a passive role in handling their affairs but rather have gained importance, both as individuals and as part of newly established groups, their need to lead and make decisions has brought effective coordination and effectiveness in agricultural water management. Therefore, establishing WUA committees that reflect the interests and inputs of scheme users is crucial to achieve fair decision making (Meinzen-Dick 2007). Local authorities and non-governmental organizations could also do more to change perceptions and behavior to reflect the importance of gender equity in sustaining the positive outcomes of irrigation at household and community levels (Yohannes et al. 2017).

Driving forces in institutional development

Understanding the driving forces of resource management at different level and organizing it accordingly is the core measure in strengthening institutional arrangements (Batchelor 1999). Batchelor (1999), in his work categorized the driving forces at farm, catchment, sub-national and national or regional scales. He classified the potential driving forces as social and biophysical driving forces and their interrelations. See Table 2.

Table 2.. Institutional driving forces adopted from Batchelor, (1999).

Scale	**Social driving forces** ↔	**Biophysical driving forces**
National and sub national level	- Commodity price	- Annual rainfall
	- Infrastructure development	- Mean annual temperature
	- Commercialization	- Seasonality
	- Migration	- Landform
		- Crop potential
	- Family structure	- Microclimate
	- Division of labor	- Season
Catchment and farm level	- Water pricing	- Soil erosion
	- Wage rate	- Altitude
	- Development work	- Topography
	- Community organization	- Drainage pattern

	- Property regime	- Soil type
	- Technology	- Vegetation distribution

Thus, irrigation organizational arrangement should understand the driving forces and their interlinkages at each scale. The multi-cultural, hydro-climatic, farming practice, and soil nature variabilities of the users should be well understood before establishing WUA institutions.

In summarizing, effective, and efficient irrigation water management will help in adopting the impacts of climate change and in achieving food security. Climate change is one of the critical elements that needs to be addressed to safeguard the environment and to feed the ever-increasing populations. In this aspect we will assess the impacts of climate change on water balance components which are the basic for irrigation water demand and supply analyses. Water balance components such as water yield, surface runoff and evapotranspiration conditions in the face of different climate change scenarios will be simulated and agricultural water management options for the study region will be sought. In addition, land use and land cover changes can affect both irrigation and the water balance and thus their analyses will also be made to fetch for optimal land use management options together with climate change.

4. Material and methods

The study methods were grouped into three categories:

A. Analyzing the impacts of climate change on the major components of the water balance in the CRVB
B. Analyzing the impacts of land use and land cover changes on the major components of the water balance in the CRVB
C. Reviewing and recommending irrigation and related resource management options based on the climate and land use change impacts

Section A. Methodologies for climate change impact analyses

4.1. Description of the study location

The Central Rift Valley Basin (CRVB) is in Ethiopia between 38°15′ E and 39°30′ E longitude and 7°10′ N and 8°30′ N latitude, Fig. 1. The study basin covers an area of approximately 9112.5 km^2. Locally, the CRVB is situated in two adjoining regions: namely, the administrative regions of Oromia and the Southern Nations Nationalities and Peoples Region (SNNPR). The mean annual rainfall of the study area varies between 600 mm near the lakes and 1200 mm – 1600 mm in the highlands. The average minimum temperature is 10.5°C, while the average maximum temperature is 24.3°C (Gadissa et al. 2018). The elevation of the area ranges from 1541 to 4184 m asl. CRVB comprises four major lakes: Ziway, Shalla, Abiyata, and Langano. It also has perennial rivers, which include the Meki, the Ketar, the Bulbula, the Horakela and the Jidu River (Gadissa et al. 2018).

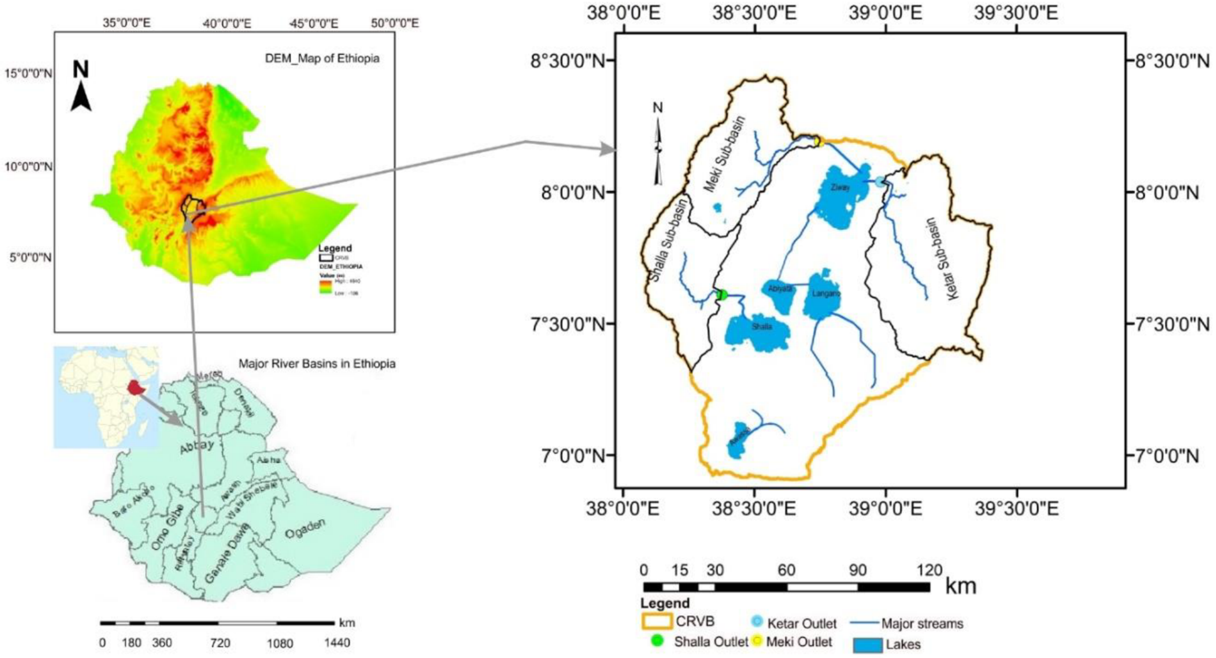


Fig. 1. Location of the study area in Ethiopia (left) and the sub-basins outlets (right).

Lake Abiyata is connected to Lake Ziway through the Bulbula River and to Lake Langano through the Horakela River. Although the basin is hydrologically a closed region, the characteristics of the lakes differ. For example, Lake Shalla is the deepest and is a closed lake with no known surface outflows from the lake. It is highly alkaline, making its water unusable for irrigation purposes. Lake Langano has a more stable water level than the other lakes in the basin. Among all the lakes, only Lake Ziway is an important element of the CRVB, because it is the only water source for irrigation and for potable water supply to the town of Ziway. It also supports fish farming, and it is a habitat for many biological diversities (Desta & Lemma 2017).

Because of the ecological, geomorphological and population growth conditions, and also because of climate change, the basin is a water-sensitive region (Gadissa et al. 2018).

The land uses and the landforms in the CRVB, including rugged mountains, a flat plain, savannah, evergreen forest, dry land masses, wetlands, lakes, together with intensive agricultural practices, industrialization, and expansion of urbanized areas, make the region unique in terms of its water resource management.

The CRVB has a vast range of land use and land cover. However, most of the land uses are categorized as agricultural land use followed by range land and forest. The details of land use and land cover are indicated in Fig. 2a. The land uses characterize the hydrological process in the sub-basins. The land use map of the CRVB was obtained from Ethiopian Geospatial and Information Institute (GSII). The land use definitions and their standard code according to SWAT land use coding is tabulated in appendix A.

The CRVB has diverse soil types, Fig. 2b. It has varying infiltrability and associated runoff potential, see Table 3. Coarse-textured soils (Leptosols) with high infiltrability are dominant in the eastern and western highlands and in the valley floor around the lakes. Medium-textured soils (Euvertisols) with moderate infiltrability dominate the eastern and western mid altitudes of the CRVB, whereas the bottom parts of the western highlands and some places in the central part of the eastern CRVB are dominated by fine-textured black soils (Vertisols) with lower infiltrability. The soil classification is based on SWAT classification standards. The climate of the CRVB is tropical, with spatial and temporal variations (Getnet et al., 2014).

Table 3. Areal coverage and some physical properties of major soils in the CRVB.

SWAT Soil Names	Area in CRVB (ha)	(%) in CRVB	(%) in Ketar	(%) in Meki	(%) in Shalla	Texture	Hydrology group	No. of layers
FLUVISOLS	55600.20	3.63	0.65	1.37	0.0	Loam	B	3
EUVERTISOLS	547949.29	35.81	33.04	22.97	14.3	Clay	D	3
LEPTOSOLS	512179.96	33.47	1.55	3.77	4.7	Loamy sand	B	2
LTLEPTOSOLS	293937.73	19.21	53.60	16.21	15.1	Sandy loam	A	1
WATER	120529.15	7.88	NA	NA	NA	Water	D	1

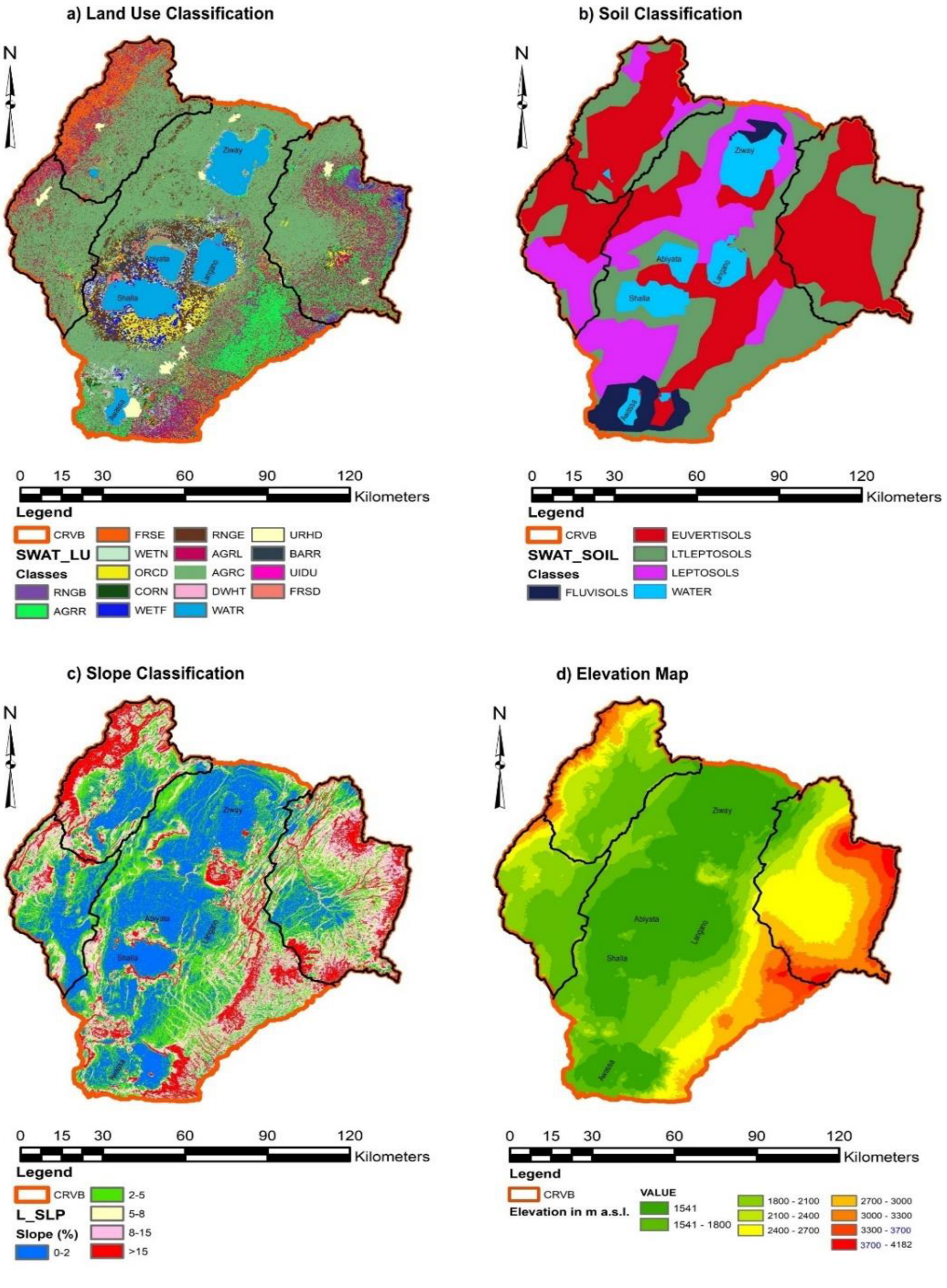


Fig. 2. Delineated maps of land use, soil, slope and elevation classes in the CRVB.

4.2. Sub-basin selection methods (Boundary delineation)

The hydrologically closed CRVB comprises many subbasins. It was delineated and subdivided into major sub-basins in GIS according to their river systems using the outlet points as indicated in Fig. 2a (Gadissa et al. 2018). The DEM data were delineated in Arc SWAT and with the spatial analyst tool in ArcGIS. The total area of CRVB was delineated based on the watershed boundaries or water divide lines obtained from Ministry of Water Resources of Ethiopia. CRVB is an endo hydrogenic basin (Getnet et al. 2014). Since there is no single outlet for the CRVB, this study aims to investigate the hydroclimatic impacts via its major sub-basins with monitored outlets (Ketar, Meki and Shalla). The selected sub-basins form parts of the CRVB with different characteristics which, when summed up, can generally characterize the climate impact conditions of the CRVB. The sub basins are selected based on differences in agro-ecology, microclimate, and socio-environmental interactions. Figs. 3 a, b, c, and d present maps of the whole CRVB with the locations of the selected sub-basins, and a soil map of each of the sub-basin. The analyses were carried out for each of the sub-basin separately. The outlet locations of each sub-basin are indicated in Fig. 4.

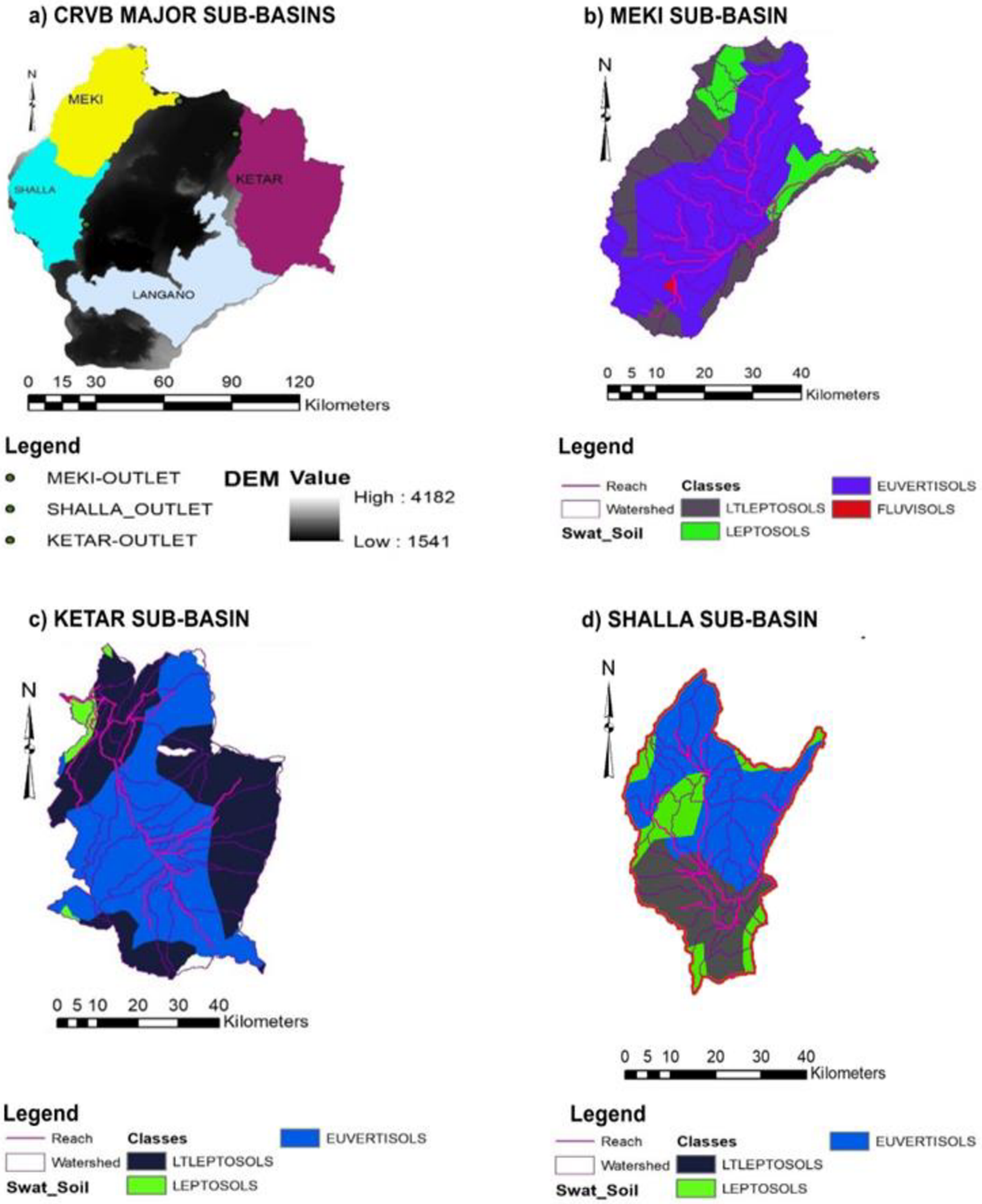


Fig. 3. Locational maps of the major sub-basins in the CRVB, and a map of each sub-basin with their soil types.

4.3. Spatial and climate data definition

4.3.1. Spatial data

The spatial data used for the study were analyzed step-by-step. In the first phase of modelling, the Digital Elevation Model (DEM) data from the study area was divided into sub-basins based on the topography and the river systems. Each sub-basin was then divided into Hydraulic Response units (HRUs) according to the land-use features, the soil profile, and the slope.

In the HRU definition, an area which comprises more than 10 % of a similar land use and more than 10 % of a similar soil profile. of the sub-basin is considered for creating a HRU, and similarly, a land slope which comprises more than 20 % of the sub-basin area is used for defining a HRU. The threshold for the slope was increased to 20 % to avoid small undulating land profiles in the sub-basins when creating the HRUs for SWAT analysis in the sub-basins.

The soil hydro-physical properties determine and define the existence and the quantity of each component of the water balance (Báťková et al. 2020). Soil physical properties are used to determine its hydraulic characteristics (Báťková et al. 2022).. Soil hydraulic characteristics, especially the soil water retention curve and hydraulic conductivity, are essential for many agricultural, environmental, and engineering applications (Matula et al. 2007). The soil physical properties and the area coverage of each soil type were classified based on the SWAT classification standards. The major data inputs and their uses are indicated in Table 4.

Table 4. The input data used in the SWAT model.

Data						
	Type	Format	Source	Year/scale	Resolution	Purpose
Weather data	Relative humidity	.xls	NMA	1984-2010	Daily	Analyze water balance (WB),
	Rainfall	.xls	NMA	1984-2010	Daily	Analyze WB & rainfall trend
	Sunshine hours	.xls	NMA	1984-2010	Daily	Analyze WB & solar radiation
	Temperature (Max &min)	.xls	NMA	1984-2010	Daily	Analyze WB, & temp trend

	Wind	.xls	NMA	1984-2010	Daily	Analyze WB, & wind trade
Spatial data	Land use	.shp	GSII	2003-2020	ha	Model land use and runoff
	Soil	.shp	MANR	NA	ha	Determine soil hydrology group
	DEM	.tiff	OBANR	2003-2008	30 m	Analyze location data sets
Hydrology data	River discharge	.xls	MW	1900-2010	Monthly average	Analyze discharge trend, for model calibration and sensitivity

Note: NMA - *National Meteorological Agency,* GSII - *Geospatial and Information Institute,* MANR - *Ministry of Agriculture and Natural Resources,* OBANR - *Oromia Bureau of Agriculture and Natural Resources,* MW - *Ministry of Water Resources.*

4.3.2. Climate data

Daily data on minimum and maximum temperature, hours of sunshine, relative humidity, wind speed and precipitation from six meteorological stations, located in and near the sub-basins, see Table 5, were introduced into the model to simulate the water balances of the region. The CORDEX grid locations in the study area, based on which the climate data were downscaled and extracted, are also presented in Fig. 4. The coordinate locations are annexed in Appendix c.

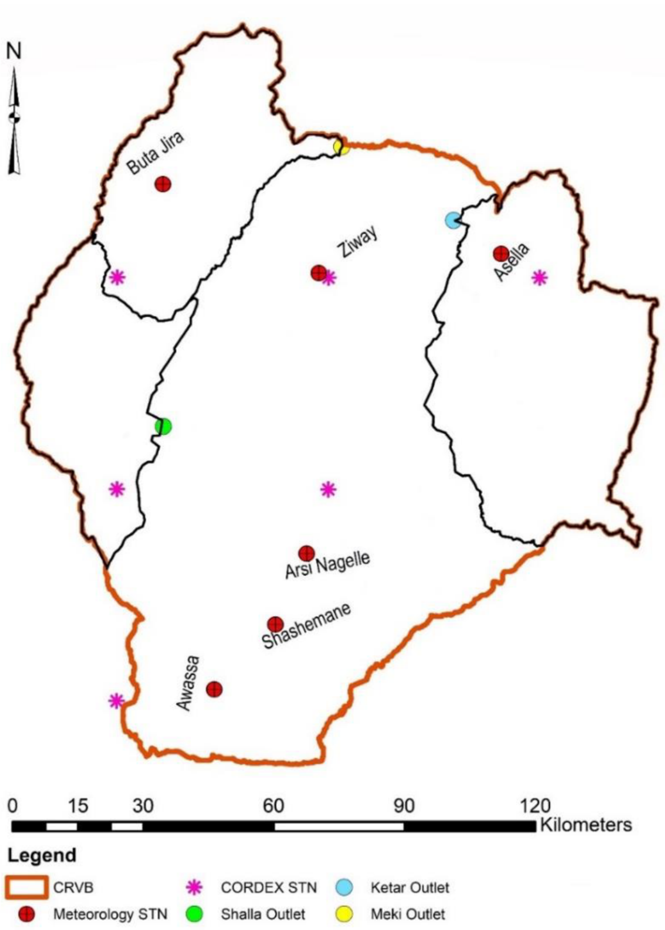


Fig. 4. Locations of meteorology stations (Meteorology STN), CORDEX grid locations (CORDEX STN) and outlets for each of the sub-basin.

4.3.3. Baseline data processing with SWAT weather generator (WGEN)

The weather data were statistically analyzed, and data qualities such as errors and outliers were assessed and adjusted by the weather database generator software (SWAT-WGEN). The data and their respective station coordinates (X, Y, and Z) were synchronized by the SWAT-WGEN. As a result, the SWAT model recognized the spatial distribution of the data supplied. SWAT-WGEN helps in statistical analyses, in data coding for SWAT use, and for data gap analyses as well as for spatial interpolation of the missed datasets. Special care was given to the input data within this study. The background data provided by the authorities were carefully checked and data gaps were filled if available. The data gaps in the collected baseline data were scattered, but on some days, they were sequential. These sequential data gaps ranged from one to only ten days maximum for some stations. The gaps were filled via interpolation by the software. These data gaps accounted for not more than 65 days out of the total 27 years per station, which is less than 0.66 % of the data items. Simple arithmetic means (taking the averages of the values of the data series available before and after the missed data dates) were also applied to those stations where the gaps were scattered and not sequential to restore the missing values.

Table 5. Meteorological stations used for the study and their coordinates in the region

No.	Station name	Latitude	Longitude	Elevation	Ownership
1	Arsi-Nagelle	7.35°N	38.68°E	1800	NMA
2	Assella	7.97°N	39.08°E	2413	NMA
3	Awassa	7.06°N	38.48°E	1694	NMA
4	Butajira	8.11°N	38.38°E	2131	NMA
5	Shashemane	7.2°N	38.61°E	1927	NMA
6	Ziway	7.93°N	38.7°E	1640	NMA

NMA- *National Meteorological Agency*

4.4. Arc SWAT application

Integrated modeling approaches for simulating the impacts of climate and land use changes were adopted for the study. Different hydrological models were assessed, and SWAT model was selected to simulate the impacts of climate change. Arc SWAT 2012 is an Arc GIS extension program used for watershed modelling. The Soil and Water Assessment Tool (SWAT) is a widely used model for analyzing the water balances of a basin using long-term meteorological and spatial data of the area (Arnold et al. 2011). It is a physically-based, deterministic, continuous, watershed-scale simulation model developed by the U.S. Department of Agriculture - Agricultural Research Service (USDA) (Arnold et al. 2011; Abbaspour et al. 2015). The model uses spatially distributed data on topography, soils, land use - land cover, land management and weather to predict water, sediment, nutrient, pesticide, and other pollutant yields (Arnold et al. 2011). It is a model written in Fortran to analyze mainly water, nutrient and sediment conditions in large basins and the behavior under climate changes (Abbaspour et al. 2015). It can also be applied to evaluate the impacts of various human, environmental, and infrastructural management interventions in basins. Applying the SWAT model involves systematic and interconnected spatial and weather data analysis to evaluate the intended goal at each Hydraulic Response Unit (HRU).

In the application of the model, the Penman-Monteith method for evapotranspiration, the Soil Conservation Service (SCS) curve number method for surface runoff determination and the variable storage method to simulate channel water routing were selected to analyze the water balances. A general flow chart of the water balance simulation processes is indicated in Fig.7. From the original Penman-Monteith equation and the equations of the aerodynamic and surface resistance, the FAO Penman-Monteith method to estimate ET_o can be derived as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0 \cdot 34u_2)} \qquad (1)$$

Where, ET_o is reference evapotranspiration [mm day^{-1}], R_n net radiation at the crop surface [MJ m^{-2} day^{-1}], G soil heat flux density [MJ m^{-2} day^{-1}], T mean daily air temperature at 2 m height [°C], u_2 wind speed at 2 m height [m s^{-1}], e_s saturation vapor pressure [kPa], e_a actual vapor pressure [kPa], e_s - e_a saturation vapor pressure deficit [kPa], Δ slope vapor pressure curve [kPa $°C^{-1}$], r psychrometric constant [kPa $°C^{-1}$] .

The SCS curve number method is a simple, widely used, and efficient method for determining the approximate amount of runoff from a rainfall event in a particular area. It is calculated as

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \qquad (2)$$

Where Q is surface runoff, P is precipitation and S is maximum retention and

$$S = \frac{1000}{CN} - 10 \qquad (3)$$

where, CN is curve number.

The variable storage method is derived from the continuity equation as variable storage per unit of changes in time is determined as inflow minus outflow.

$$I - O = \frac{dS}{dt} \qquad (4)$$

where I [m^3/s] and O [m^3/s] are the inflow and outflow rate for a river reach, respectively, t [s] is the time, S [m^3] is the storage (Abbaspour et al. 2015).

4.4.1. The water balance equations

In the analysis of the impacts of climate change on water balance components, the model operates on the basis of the water balance equation i.e., the discharge simulated by Arc-SWAT is based on a water balance equation (Arnold et al. 2011) and is defined as:

$$SWt = SW_0 + \sum_{i}^{t} (Rday_i - Qsurf_i \; - Ea_i \; - Wseep_i \; - Qgw_i) \qquad (5)$$

Where: SWt is soil water content [mm] at time t, SW_0 is initial soil water content [mm], t is simulation period [days], $Rday_i$ is amount of precipitation on the i-th day [mm], $Qsurf_i$ is amount of surface runoff on the i-th day [mm], Ea_i is amount of evapotranspiration on the i-th day [mm], $Wseep_i$ is amount of water entering the vadose zone from the soil profile on the i-th day [mm], and Qgw_i is amount of base flow on the i-th day [mm].

One of the critical parameters that are evaluated for sustainable water resource management of the study area is the water yield. The water yield is the aggregate sum of water leaving the HRU and entering the principal channel during a time step (Arnold et al. 2011). The water yield within a basin is evaluated by the model based on Eq. (2). Considering the hydrological processes taking place continuously in the basin, the water yield, i.e., the net amount of water flowing past a given point on a stream during a given period, can be described by a basic model equation:

$$W_{yld} = \; Q_{sur} + Q_{lat} + Q_{gw} - T_{loss} \qquad (6)$$

where: W_{yld} is the water yield [mm], Q_{sur} is the surface runoff [mm], Q_{lat} is the contribution of the lateral flow to the stream [mm], Qgw is the contribution of the groundwater to the streamflow [mm], and T_{loss} is the transmission losses [mm] from the tributary in the HRU by means of transmission through the bed.

4.4.2. Model parameter sensitivity analyses

For a particular site, Arc-SWAT contains many hydrological parameters that need to be calibrated. However, not all the parameters may be contributing significantly to the model output, and it is therefore necessary to identify the input parameters that are significant for the site in streamflow simulations (Abbaspour et al. 2015). In addition, the heterogeneity of the sites makes it difficult for all SWAT parameters to be monitored simultaneously. Calibration and validation also help to identify the parameters to use for the specific area in a balanced way (Teshager et al. 2016).

The parameter sensitivity scale developed by Lenhart et al. (2002) is used to classify the sensitivity of the parameters in the sub-basins. Table 6 presents the sensitivity scale or the index class developed by (Lenhart et al. 2002).

Table 6. Parameter sensitivity scale adopted from Lenhart et al. (2002).

Class	Mean of index (I)	Category of sensitivity
1	$0 \leq I \leq 0.05$	Small to negligible
2	$0.05 \leq I \leq 0.2$	Medium
3	$0.2 \leq I < 1$	High
4	$I \geq 1$	Very high

The identified parameters and their decriptions are tabulated in Table 7.

Table 7. Identified sensitve SWAT parameters in the sub-basins and their descriptions.

	Parameter	Description
1	CN2	SCS runoff curve number
2	ALPHA_BF	Base flow recession constant [days]
3	GW_DELAY	Ground water delay time for recharging the aquifer [days]
4	GWQMN	Water limit level in the aquifer for the occurrence of base flow [mm]
5	REVAPMN	Water limit level in the aquifer for revap to occur [mm]
6	GW_REVAP	Groundwater revap coefficient
7	ESCO	Soil evaporation compensation factor
8	EPCO	Plant uptake compensation factor
9	SURLAG	Delay time of direct surface runoff [days]
10	SOL_AWC	Available water capacity of the soil layer [mm mm^{-1}]
11	SOL_K	Saturated hydraulic conductivity of the soil [mm h^{-1}]
12	CH_K2	Effective hydraulic conductivity of the main channel [mm h^{-1}]
13	SOL_Z	Depth from soil surface to the bottom of the layer [mm]
14	RCHRG_DP	Deep aquifer percolation fraction
15	HRU_SLP	Average slope steepness [m m^{-1}]
16	BIOMIX	Bio-mixing efficiency

The most sensitive parameters used for stream flow analyses in the CRVB are selected on the basis of a tropical nature environment and review recommendations (Setegn et al. 2008). The sensitivity ranking of the parameters, I, is defined through an analysis of the values of the "t-stat" and "p-value" indexes in SWATCUP during calibration. The "t-stat" values are the t statistics.The t statistics is a measure of how extreme a statistical estimate is, and is calculated as:

$$t = \frac{M - \mu}{S_m} \qquad (7)$$

Where: t = t-stat, M = sample mean, μ= population mean and S_m = estimated standard error.

4.4.3. Model calibration and validation

The model was calibrated and validated using monthly monitored stream flows from the outlets of the Ketar River, Meki River and Jidu River. The outlet locations were set at the flow gauging stations. Calibration and validation of the SWAT model were performed with the use of SWAT-CUP, a calibration uncertainty program for SWAT with the SUFI-2 algorithm. The models were set to run for the baseline periods from 1984 to 2010 for each of the sub-basins (Ketar, Meki, & Shalla).

Calibration and validation help the model to resemble the study area in its operation by adjusting the sensitive model parameter values. In this study, the monthly observed stream flow data from 1990 to 2001, obtained from the Ministry of Water Resources of Ethiopia (MoW), were used for calibration, and data from 2004 to 2010 were used for validation. The models of each sub-basin were calibrated and validated separately with their respective stream flow data from each sub-basin outlet, Fig. 3. In each sub-basin, the data from the first three years were kept as a warming-up period. These data allow the model to warm up, initialize and approach reasonable initial values of the state variable of the model ("SWAT" n.d.). The calibration and the uncertainty analysis were carried out using Sequential Uncertainty Fitting version-2, (SUFI-2), a calibration algorithm developed by Abbaspour et al. (2004, 2007) for calibrating the SWAT model.

4.4.4. Model performance evaluations

Three main statistical parameters were used to evaluate the performance of the model: the Coefficient of Determination (R^2), the Nash-Sutcliffe Efficiency (*NSE*), and the Percentage of Bias (*PBIAS*) (Das et al. 2019).

R^2 is calculated as:

$$R^2 = \left[\frac{\sum_{i=1}^{N}(O_i \ - O)(S_i \ - S)}{\left[\sum_{i=0}^{N}(O_i - O)^2\right]^{0.5}\left[\sum_{i=0}^{N}(S_i - S)^2\right]^{0.5}}\right]^2 \qquad (8)$$

R^2 ranges from 0.0 to 1.0. A higher value of R^2 indicates better performance of the model. Where, S is the mean of the simulated stream flows, O is the mean of the observed stream flows, S_i is the simulated stream flows, O_i is the observed stream flows, and N is the number of observations. It holds same for equation 9 and 10.

The formula for calculating NSE is:

$$NSE = 1 - \frac{\sum_{i=1}^{N}(O_i - S_i)^2}{\sum_{i=1}^{N}(O_i - O)^2} \qquad (9)$$

Nash-Sutcliffe Efficiency (*NSE*) is the normalized statistics, which measures the relative magnitude of the residual variance in comparison with the variance of the measured data. Like R^2, the higher the value of *NSE*, the better the performance of the model. *NSE* indicates the statistical relationship between simulated model values and observed values. Das et al., 2019 state that the "values of *NSE* vary from $-\infty$ to 1."

PBIAS is calculated as:

$$PBIAS = \frac{\sum_{i=1}^{N}(S_i - O_i)}{\sum_{i=1}^{N} O_i} \ X\ 100 \qquad (10)$$

PBIAS measures the average tendency of the simulated values to be larger or smaller than their respective observed values. Positive *PBIAS* values indicate underestimation by the model, and negative values indicate overestimation. From the general statistics, the range within ±25% is acceptable.

4.5. The climate scenario application and analysis methods

4.5.1. Climate scenario analyses setting and simulation

An Arc-SWAT-based modeling approach to analyzing the impacts of climate change in the sub-basins of the CRV lakes region, and optimum agricultural water use and optimization strategies with respect to the identified impacts were carried out. Separate modeling for the selected sub-basins was performed. The climate scenarios (CSc) were set to analyze the impacts of climate change on the components of the water balance in the near-term (2031–2060) and in the long-term (2070–2099) periods for each of the regional concentration pathways (RCP) emission scenarios. The emission scenarios are RCP2.6 (low emission scenario), RCP4.5 (medium emission scenario), and RCP8.5 (high emission scenario). The simulations were categorized into seven CSc analyses, including the baseline data as listed in Table 8. The options for agricultural water use management are indicated based on the resulting water balance components affected by the changes in climate for each sub-basin.

The climate data were downscaled, bias corrected, analyzed, and simulated in an integrated manner with WGEN, CMhyd, and Arc SWAT. The WGEN software interlinks station coordinates and elevations with their respective data. All data statistics, such as average, standard deviation, mean, variance, etc., for each of the weather components downscaled were calculated and synchronized to their respective stations with WGEN. Rain Years, dew point, and other important variables useful for calculating the water balance components were also calculated and generated in WGEN. Finally, these climate data were imported into the SWAT models and simulated to see the changes in the components of the water balance that are especially useful for surface water sources.

4.5.2. Data downscaling

Climate data stored in the World Climate Research Program (WCRP) databases were used. The data are from the experiments of CMIP5–RCP (RCP2.6-CMIP5, RCP4.5-CMIP5, and RCP8.5-CMIP5). These data were derived by the MIROC-RCA4 ensemble driving climate models under the GCM. The GCM data of these RCP data variables were regionalized to the regional climate model (RCM) with the Coordinated Regional Downscaling Experiment (CORDEX) for Africa, CORDEX-AFR-44. Both, historical data as well as the data of RCP2.6, RCP4.5, and RCP8.5 were downscaled by RCA4 models. RCA4 is the fourth version of the Rossby Center Regional Atmospheric model. It was originally developed by the Swedish Meteorological and Hydrological Institute within the CORDEX initiative. It is a dynamic downscaling method widely used with the CORDEX (Musie et al. 2020b). The downscaled datasets were daily precipitation, daily maximum near-surface air temperature, daily minimum near-surface air temperature, daily sunshine duration, near-surface relative humidity, and near-surface wind speed for future periods from 2006 to 2100. The duration of daily sunshine in units of second (s) was extracted from the model and adjusted to daily solar radiation with the units of kilowatt per square meter (kW/m^2) for SWAT use and to the SWAT input data standard units using Angstrom techniques (Argaw 2007).

4.5.3. Bias correction

The data for precipitation and temperature were bias corrected via linear scaling methods with CMhyd software, which is a SWAT community tool, before they were applied in the SWAT simulation. The need for bias correction is mainly due to onshore and offshore trade wind disturbances. The historical data from the model and the observed locational dataset from six stations in the study region were applied to the software. Data ranges from 1990 to 2006 were applied from the historical dataset of the climate model. Furthermore, observed datasets from the same periods were used to correct the biasedness created due to trade winds in the climate models. Parameters or correction factors for each month were developed in relation to the observed data range of the same time periods. Based on the parameters, the software adjusted the predicted rainfall and temperature values from the downscaled data. The corrected data values were applied to WGEN for statistical analyses and then to SWAT for simulation.

Table 6. Applied climate scenarios used for analyzing the impacts of climate change on the major components of the water balance in the sub-basins.

Climate Scenario		
No.	Code	Description (Years)
1	NT-RCP2.6	RCP2.6 (2031-2060)
2	LT- RCP2.6	RCP2.6 (2070-2099)
3	NT-RCP4.5	RCP4.5 (2031 -2060)
4	LT- RCP4.5	RCP4.5 (2070-2099)
5	NT-RCP8.5	RCP8.5 (2031 -2060)
6	LT-RCP8.5	RCP8.5 (2070-2099)
7	BD	Observed baseline data (1984-2010)

Note: NT= *Near term* and LT-*Long term*.

5. Materials and methods - Section B. Methodologies for the LULC change impact analyses

5.1. Description for the LULC of the study area

CRVB is in East Africa region and located in the upper head of the rift valley basin in Ethiopia, (Fig. 5). It is part of the main Ethiopian rift comprises a significant part of the great African rift valley system that stretches from the Red Sea to Mozambique passing through Ethiopia, Kenya, and Tanzania. In Ethiopia, it is divided into three subsystems: Chew Bahir (Lake Stephanie), CRV, and Afar triangle (Elias et al. 2019).

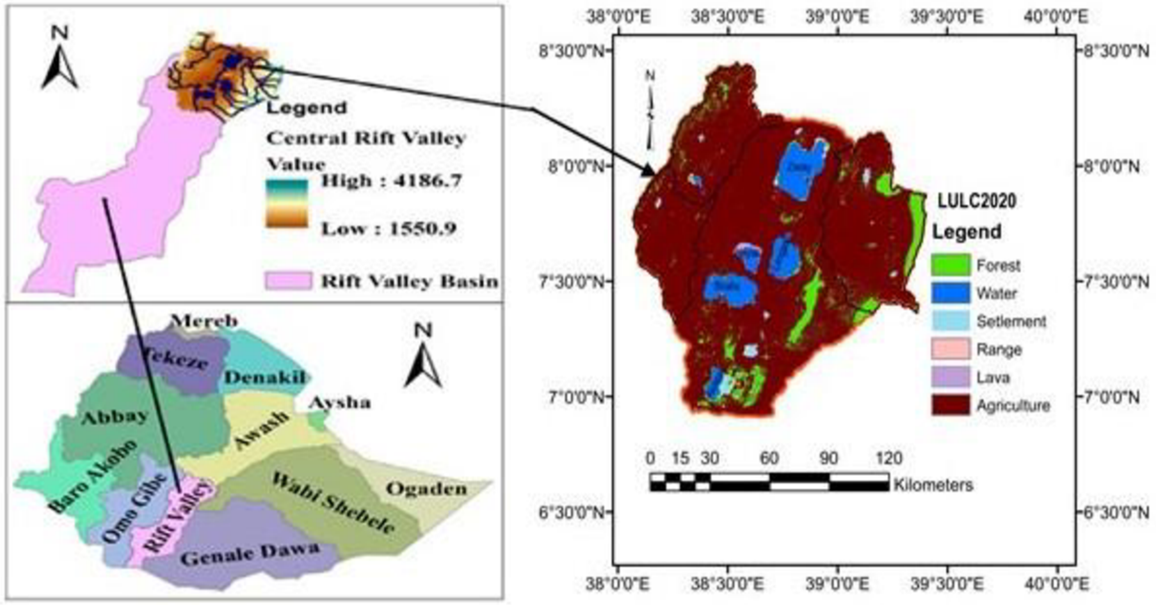


Fig. 5. Major river basins in Ethiopia (left bottom), location of CRVB (left up) as adopted from Gadissa et al. (2019) and LULC of the year 2020 (right).

To build model input files, SWAT-2012, requires a digital elevation model (DEM), land cover and land use information, soils, and basic climate data. SWAT subdivides a watershed into individual hydrologic response units (HRU) and treats the HRU as a homogeneous block of land use, management techniques, and soil properties and then quantifies the relative impact of vegetation, management, soil, land use and climate changes within each HRU (Arnold et al. 2011). Subdividing the watershed allows users to analyze hydrologic processes in different sub-basins within a larger watershed and help to understand regionalized land use change impacts.

Accordingly, CRV basin was sub divided into sub-basins based on their outlet points as indicated in Fig.5. Basic climate data such as the daily observed precipitation, maximum and minimum temperature, wind speed, sunshine hour, and relative humidity data of six stations in CRV regions were collected from the National Meteorological Agency (NMA) of Ethiopia. Hydrology data of river discharge at three stations were obtained from Ministry of Water and Energy (MW&E) of Ethiopia for calibration and validation of the SWAT model (Table 4).

Land cover and land use maps used were obtained from Ethiopian Geospatial Information Institute (GSII). Land cover and land use based on Landsat TM and ETM+ and Sentinel satellite imagery from 2003, 2008, and 2013 and 2020 was mapped. They were able to map into major LULC such as rangelands and shrubs, forest, agricultural land, urban and settlements, and water at each time step. Land use data that are adjusted based on ground truth points for the years of 2003, 2008, 2013 and 2020 were thus used to analyze the impacts of land use change on the components of the water balance in the region.

The soil data map to determine soil parameters, such as texture, hydrologic soil group (HSG), and available water content for soils as needed to run SWAT were obtained from Ministry of Agriculture (MoA) and DEM data were from Oromia Bureau of Agriculture and Natural Resources (OBANR) (Table 4).

5.2. Land use and land cover change processing

5.2.1. Sub-basin delineation and land use reclassification

The CRV region was classified into sub-basins based on their discharge outlet (monitoring) stations. Three of the major sub-basins such as Ketar, Meki and Shalla, (Fig.5), were delineated with SWAT HRU tools and Arc- GIS to analyze and quantify the hydrological impacts of the past LULC changes as well as the future potential change impacts with a calibrated SWAT model. The major LULC of the sub-basins were classified into Agriculture, Forest, Rangeland, Water, and Settlements based on their hydrologic response similarities (Wagener et al. 2007; Sawicz et al. 2011). Thus, the classified LULC categories were presented in Table 9. The maps of the reclassified LULC were also indicated in Fig. 6 for each time-steps in the past.

Table 7. Descriptions of the reclassified LULC of the CRVB.

Object Id	Class	Description	LANDUSE Code
1	Agriculture	Cultivated land; rainfed; irrigated, cereal land cover system; vegetables, fodder crops	AGRR
2	Range	Shrubland; Open (20-50% woody cover); grass land, forested brush's, scattered stone, wood lands	RNGE
3	Forest	Forest; montane, mixed, dense (50-80% crown cover), ever green, orchards, deciduous, plantations.	FRST
4	Settlements	Urban, residential areas, roads, industrial zones, barren land, dry sand, and dry stream channels, bed rocks, dry land mass and lava outflows.	URHD
5	Water	Rivers, lakes, ponds, and wetlands	WATR

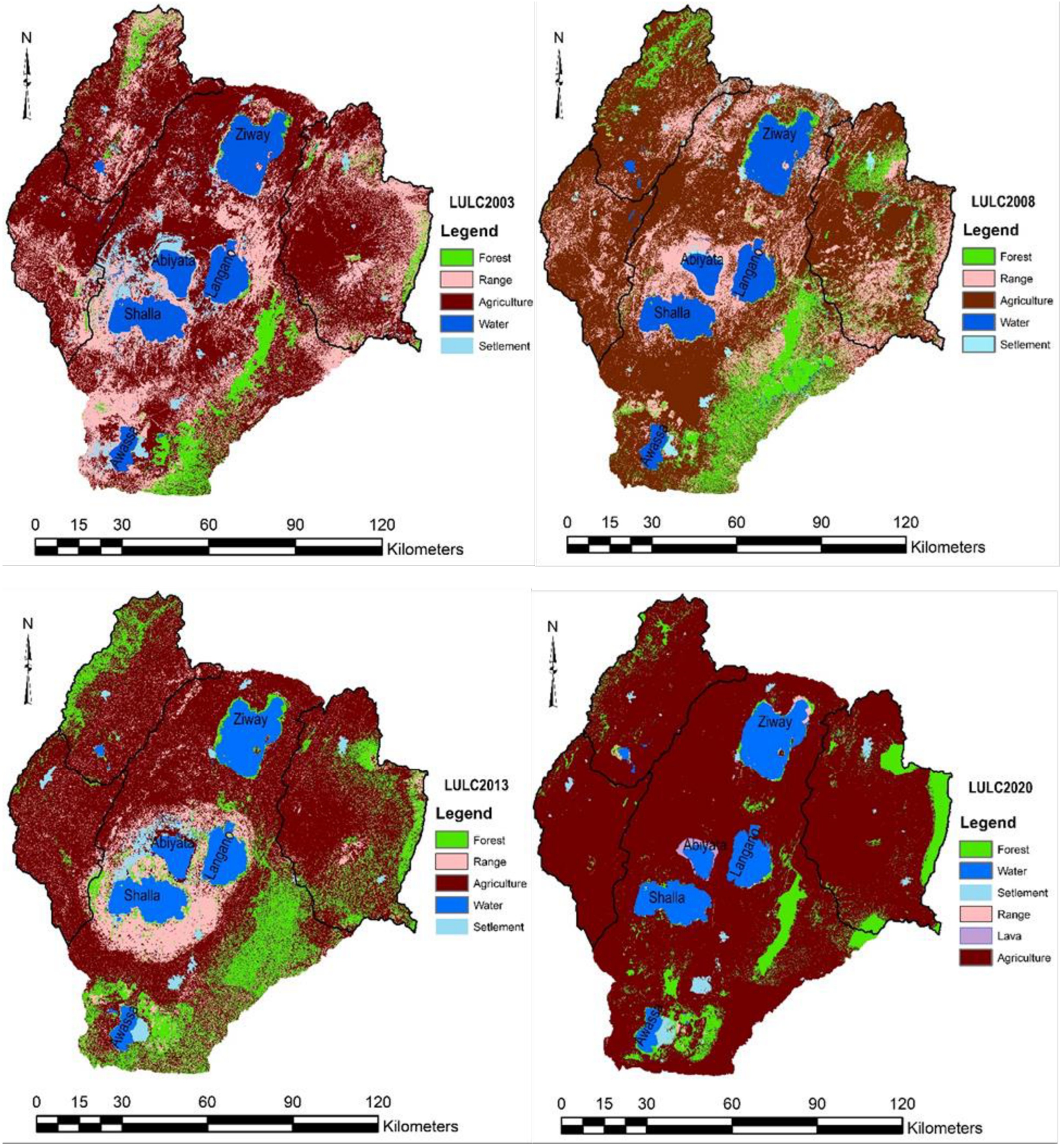


Fig. 6. Maps of the past classified LULC of the CRVB for each time steps.

5.3. Past LULC change analyses and future prediction methods

5.3.1. Past land use and land cover change analyses

The quantification and evaluation of changes of each LULC categories were analyzed with SWAT model and with Land Change Modeler (LCM) embedded in TerrSet 2020. In the SWAT model, the area coverage of each LULC categories in each sub-basin were calculated with HRU analysis tool. HRU tool calculates the static area coverage of the supplied land use map as categorized for a defined period, like year 2013 or year 2020.

However, the LCM will calculate the percentage of gains and/or loses in areas of each land use categories between the two-time steps. The change evaluation will be done for the whole area of the two supplied maps that were georeferenced exactly to indicate same place but with different time periods. Thus, the dynamics of each LULC categories of the sub-basin between two defined time periods were analyzed.

5.3.2. Land use and land cover change prediction

The predicted land uses were done by LCM in TerrSet2020, a geospatial monitoring and modelling system. TerrSet 2020 is an integrated model developed in Clark University Lab, USA, for geospatial monitoring, evaluation, and modelling. In the analysis, LCM determines the dynamics of LULC change, how much land cover change took place between earlier and later LULC images, and then calculates a relative number of variable transitions. The LCM is used to predict and project changes using multiple land cover categories. The LCM in TerrSet model uses Cellular Automata-Markov Chain (CA_MC) which is a stochastic modeling method used to simulate the future LULC change over time from past changes (Leta et al. 2021a; “Land Change Modeler in TerrSet” n.d.). It predicts the spatial structure of various LULC categories and scenarios based on the Transition Potential Matrix (TPM).

The LCM has three sub functions such as the change analysis, the transition potentials, and the change prediction categories together with many other sub functions. The change analysis sub suction analyzes the trend of spatial changes and creates maps. The transition potential sub section helps to simulate the future potential transition scenarios. The change prediction sub suction predicts the land cover and validates the predicted land cover based on the transition scenarios developed under transition potential. The LCM uses different approaches to produce maps of transition potential. In this analysis, a multi-layer perceptron (MLP) approaches were selected. It is more flexible, and dynamic compared to the others when multiple transition types are modeled. In the prediction section, Markov chain was used to generate transition probability matrices between LULC classes. LCM predicts the possible land use that would occur in the future based on past land use changes according to transition potential scenarios and the sub-model analyses.

5.3.3. LCM validation

Validation is a process to assess the quality of the predicted LULC map against a reference map (Leta et al. 2021b). The images of Landsat for 2008 and 2013 were utilized after its categories were harmonized to simulate the 2020 LULC image. The comparison of simulated LULC image with the actual map was developed. The LULC of the 2008 and 2013 years were provided to validate LCM, and the model was validated against the recent LULC map of 2020. The validation process in LCM involves a cross-tabulation in a three-way comparison between the earlier land cover map (2008), the predicted land cover map (2020), and the actual map (2020). The module validation in the LCM model was used to assess statistically the quality of the predicted 2020 LULC image against the 2020 reference image.

5.4. The LULC change impact analyses on the components of the water balance (a fixing-changing method)

Understanding the watershed response to LULC changes is important for water resources management. Accordingly, the classified (2003, 2008, 2013 and 2020) and the predicted (2030, 2040 and 2050) LULC maps were used to uncover the hydrologic impacts of LULC changes. The LULC maps were used separately while all other SWAT inputs were kept similar. A “fixing-changing method”, meaning changing LULC maps while keeping other inputs constant in the SWAT model to quantify the impacts of LULC. These methods were employed by many researchers (Woldesenbet et al. 2017; Gashaw et al. 2018; Chauhan et al. 2020). The changes in water balance components were analyzed in relation to the water balance outputs of the land use data used during SWAT calibration and validations which is the LULC data of the year 2003. The general flow chart of the methods was indicated in Fig. 7.

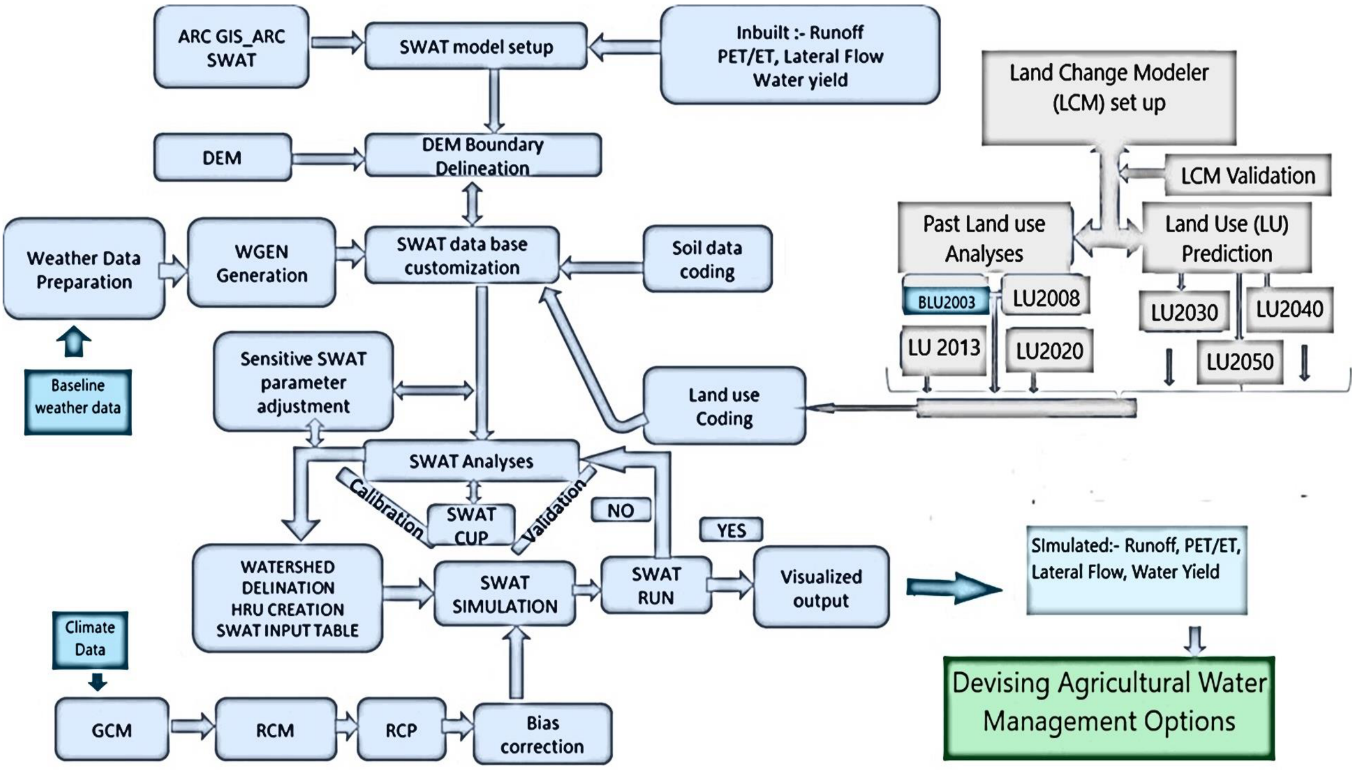


Fig. 7. Graphical illustration of the study methodologies.

6. Results and Discussion - Section A. Results for the impacts of climate change

6.1. Results for model parameters sensitivity analyses

The sensitivity analysis was carried out together with the calibration process, as it is necessary to include the flows estimated by SWAT and the monitored flows in the sub-basin. In this study, NSE was the main objective function against which the model was evaluated. In general, higher "t-stat" and a lower P-value indicate that the parameter is sensitive (Moreira et al. 2018). Based on the sensitivity scale developed by Lenhart et al. (2002), parameters EPCO, RCHRG_DP, SOL_K, GW_DELAY, CN2, REVAPMIN, and SURLAG were identified as very highly sensitive parameters in the Ketar sub-basin. Similarly, ESCO, REVAPMIN, GWQMN, HRU_SLP and GW-DEALY were very highly sensitive parameters in the Meki sub-basin, and ESCO, CH_K2, SOL_K, GWQMN were very highly sensitive in the Shalla sub-basin. An overview of all parameters and of their sensitivity based on the "t-stat" values for the Ketar, Meki and Shalla sub-basins are presented in Table 10. The differences in the sensitivity of the hydrological parameters in the sub-basins indicate that the sub-basins are heterogeneous, though they refer to a single closed lakes region. The hydrological management of the sub-basins should therefore take these variabilities into consideration.

Table 8. Sensitivity index (I) or "t-stat" values of the parameters.

	Ketar		**Meki**		**Shalla**	
Parameter	t-stat value	Sensitivity	t-stat value	Sensitivity	t-stat value	Sensitivity
R__CN2.mgt	1.408	Very high	-0.394	Negligible	-0.111	Negligible
V__ALPHA_BF.gw	0.046	Low	-0.997	Negligible	-1.643	Negligible
A__GW_DELAY.gw	1.206	Very high	1.951	Very high	-1.032	Negligible
A__GWQMN.gw	0.783	High	1.564	Very high	2.685	Very high
A__REVAPMN.gw	1.970	Very high	1.441	Very high	-1.116	Negligible
A__GW_REVAP.gw	0.710	High	0.844	High	NI*	NI*
V__ESCO.bsn	0.905	High	1.181	Very high	1.739	Very high
V__EPCO.bsn	1.013	High	-1.210	Negligible	-1.513	Negligible
A__SURLAG.bsn	2.329	Very high	-1.242	Negligible	0.744	High
R__SOL_AWC(..).sol	-1.034	Negligible	-3.957	Negligible	NI*	NI*

R__SOL_K(..).sol	1.202	Very high	-1.417	Negligible	1.197	Very high
V__CH_K2.rte	-0.551	Negligible	NI*	NI*	1.926	Very high
R__SOL_Z(..).sol	NI*	NI*	NI*	NI*	NI*	NI*
V__RCHRG_DP.gw	1.137	Very high	NI*	NI*	-1.986	Negligible
R__HRU_SLP.hru	NI*	NI*	1.799	Very high	0.084	Low
R__BIOMIX.mgt	NI*	NI*	1.669	Very high	0.798	High

**Note:* NI=*not identified,*

6.2. Results of the calibration and validation of the model

The calibration results indicated good agreement between the simulated and observed monthly discharges in the sub-basins. The results for simulated and observed monthly discharges in the sub-basins were evaluated against R^2, *NSE and PBIAS* during calibration and validation. The values in the Ketar sub-basin are in good agreement with $R^2 > 0.6$, $NSE > 0.5$ *and* $PBIAS \leq \pm 25$. Similarly, the results show that the simulated and observed monthly discharges were in good agreement during calibration and validation for the Meki and Shalla sub-basins, (Table 11).

Table 9. Outputs of the model performance analyses in the sub-basins.

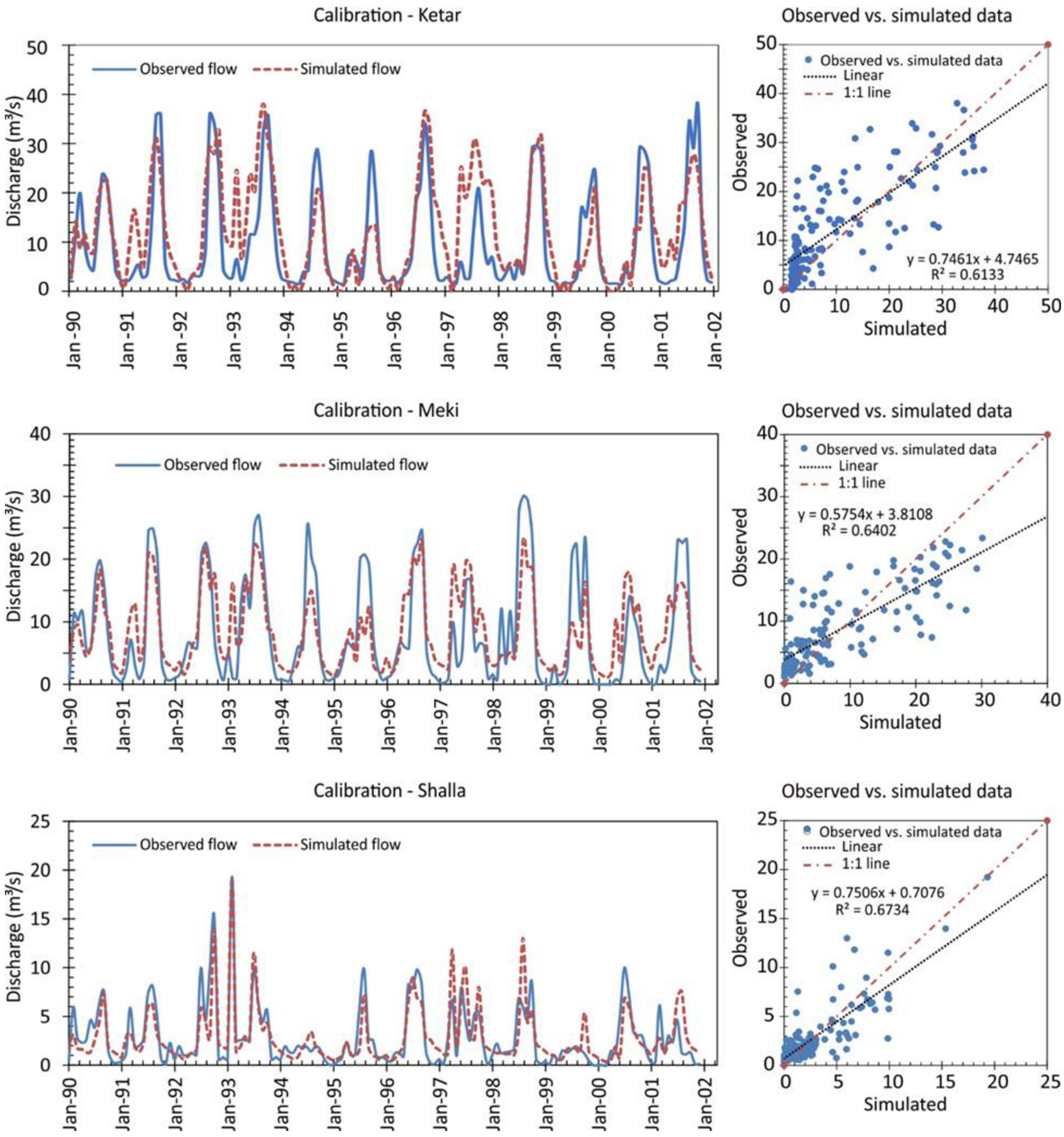
Sub-basin	**Calibration statistics**			**Validation statistics**		
	R^2	NSE	PBIAs	R^2	NSE	PBIAs
Ketar	0.64	0.54	-22.5	0.85	0.84	-2.6
Meki	0.67	0.63	-4.81	0.72	0.64	-32.17
Shalla	0.67	0.66	0.2	0.77	0.74	1.34

Calibration results for the Ketar, Meki and Shalla sub-basins are presented graphically in Fig. 8a, and validation results are presented in Fig. 8b. In calibration and validation, the SWATCUP program adjusts the model parameter values. The adjusting parameter values as adjusted by SWATCUP are tabulated in Table 10. The adjusting methods are indicated as aprefix to the parameters identified during caibration and validation. The description for each prefix is indicates at the foot note table 10.

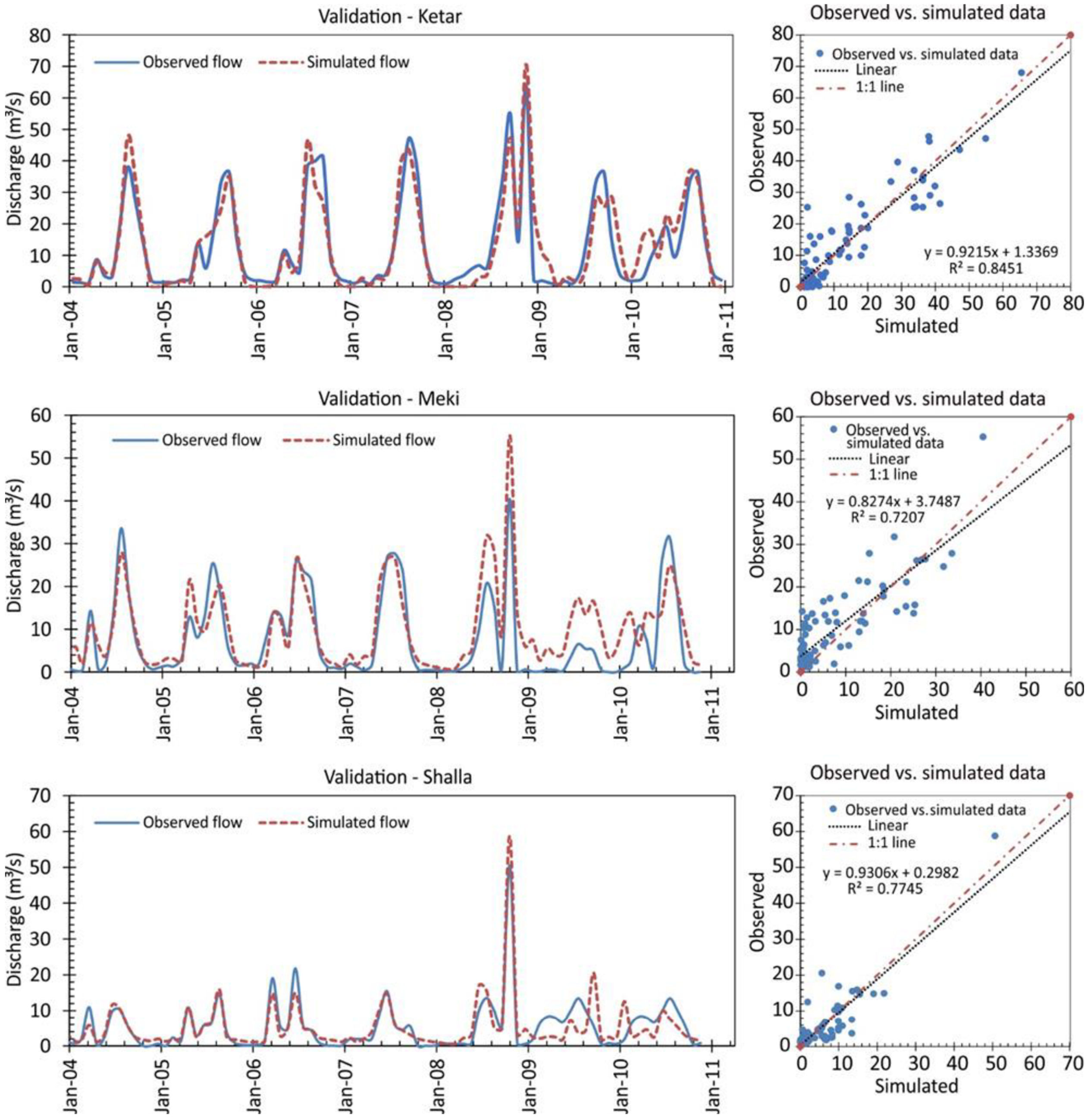
Table 10. Adjusting values and methods as adjusted by the SWATCUP for the parameters.

Ketar		**Meki**		**Shalla**	
Parameter	Adjusting value	Parameter	Adjusting value	Parameter	Adjusting value
R__CN2.mgt	-0.44	R__CN2.mgt	-0.586	R__CN2.mgt	-0.155
V__ALPHA_BF.gw	0.629	V__ALPHA_BF.gw	0.348	R__ALPHA_BF.gw	-0.35
A__GW_DELAY.gw	12.251	A__GW_DELAY.gw	-17.291	A__GW_DELAY.gw	3.283
A__GWQMN.gw	336.23	A__GWQMN.gw	109.676	A__GWQMN.gw	-819.543
A__REVAPMN.gw	13.917	A__REVAPMN.gw	-126.446	A__REVAPMN.gw	213.915
A__GW_REVAP.gw	0.0403	A__GW_REVAP.gw	0.143	V__GW_REVAP.gw	0.18
V__ESCO.bsn	0.98	V__ESCO.bsn	0.43	V__ESCO.bsn	0.412
V__EPCO.bsn	0.221	R__EPCO.bsn	-0.662	V__EPCO.bsn	0.417
A__SURLAG.bsn	20.086	A__SURLAG.bsn	16.174	V__SURLAG.bsn	25.349
R__SOL_AWC(..).sol	1.29	R__SOL_AWC(..).sol	1.274	R__SOL_AWC(..).sol	NA*
R__SOL_K(..).sol	-0.661	R__SOL_K(..).sol	0.166	R__SOL_K(..).sol	0.149
V__CH_K2.rte	79.915	V__CH_K2.rte	NA*	A__CH_K2.rte	-74.91
R__SOL_Z(..).sol	0.665	R__SOL_Z(..).sol	NA*	R__SOL_Z(..).sol	NA*
R__RCHRG_DP.gw	-0.122	V__RCHRG_DP.gw	NA*	V__RCHRG_DP.gw	0.093
R__HRU_SLP.hru	NA*	R__HRU_SLP.hru	0.783	R__HRU_SLP.hru	NA*
R__BIOMIX.mgt	NA*	R__BIOMIX.mgt	0.205	R__BIOMIX.mgt	NA*

Note: R = *relative, the parameter will be multiplied by the relative value as follows: value* (1+R)*
V = *replace, the parameter value will be replaced by the new values in the model*
A = *absolute, the parameter value will be added to the values in the model as follows: value+A*
NA* = *unchanged default values in the model*



a) calibration.



b) validation

Fig. 8 a) & b). Calibration (a) and validation (b) results of the models for the sub-basins.

6.3. Climate scenario analyses results and discussion

The results of the impacts of climate change on the major components of the water balance such as surface runoff (Q), water yield (WY) and evapotranspiration (ET) were evaluated in terms of their annual, seasonal, and monthly variations. The Q, WY and ET were identified as the most sensitive elements of the water balance components in the CRVB. The simulated impacts of the climate scenarios on the water balance components are substantial. The percentage change of the Q, WY, and ET from their baseline simulated outputs for each sub-basin are presented in Table 13, together with the indication of the baseline annual rainfall data (averaged for years 1984 – 2010).

Table 11. The simulated mean annual changes, as a percentage, from the annual average values of the baseline outputs for the major components of the water balance in the sub-basins.

Sub-basins		**Ketar**			**Meki**			**Shalla**		
Annual average rainfall (mm)			798.1			674.4			713.4	
Water balance components		Q	WY	ET	Q	WY	ET	Q	WY	ET
Baseline annual average (mm)		103.8	492.2	282.5	53.5	257.5	393.1	44.2	326.7	363.8
			% of Δ							
Scenarios	NT-RCP2.6	-62.2	-34.9	17.3	58.1	17.0	4.5	-3.5	0.9	12.2
	LT-RCP2.6	-55.0	-30.3	13.3	60.2	19.9	2.6	31.6	12.0	9.3
	NT-RCP4.5	-13.7	-35.9	-4.1	6.0	-1.1	5.6	-21.9	-10.1	9.2
	LT-RCP4.5	22.9	-28.7	-9.4	47.7	11.2	2.6	32.8	4.2	7.8
	NT-RCP8.5	-65.2	-42.2	7.4	58.3	13.0	6.4	-7.7	-2.4	10.8
	LT-RCP8.5	-60.5	-39.7	8.8	85.8	23.9	9.4	23.5	7.1	15.1

Note: % of Δ = *Percentage of change of annual mean of the components from their baseline annual averaged output*

6.3.1. Ketar sub-basin

The resulting simulated ET, WY, and Q mean monthly values for the Ketar sub-basin are graphically displayed in Figure 9. The result indicates that there are changes in the Q pattern over the seasons in the sub-basin. The highest Q season has shifted both in near and long terms of RCP4.5 to the months from March to May while it used to be from mid-June to the end of September in the observed data simulations, as shown in Fig.9. The simulated annual variations from the base data are between -65.2 % (LT-RCP8.5) and 22.9 % (LT-RCP4.5). RCP 2.6 and RCP 8.5 analyses indicate that the expected runoff will decrease both in the near term and in the long terms in relation to the base data simulations. In all the seasons, for all RCPs, the runoff condition in the long-term (LT) is higher than the runoff in the near term (NT) periods. However, the general trend indicates that the runoff is decreasing in this sub-basin in relation to the baseline period, but the rate of its reduction differs from one RCP to another and from one period to another.

In similar analyses, the WY in the Ketar sub-basin decreases for all RCPs' both in the NT & LT periods except in the long-term periods of RCP4.5 for the months from April to June, see Fig.9. Generally, the impact is expected to reduce the WY in all projected scenarios, especially for the periods from July to October. However, the rate of reduction varies from RCP to RCP and varies from season to season, see Fig.9. Nevertheless, the annual WY generation capacity of the Ketar sub-basin is higher than in the Meki & Shalla sub-basins, corresponding to the annual precipitation that is supplied. Almost half of the rainfall, 50 % on an average, goes to the WY in all the scenarios, while the proportion is about 40 % in the Meki sub-basin and about 44 % in the Shalla sub-basin. The simulated WY in the RCPs follows a similar pattern to the observed base year simulations. It means that the seasonal change in WY is not disturbed in pattern but in quantity.

The ET in the sub-basin has bi-annual peaks between March and mid-May, and between July and September, see Fig.9. The ET is relatively low between mid-May and June. The rate of ET decreases between March and May in all the scenarios in relation to the observed data simulations except between June and September. ET will be higher in the Ketar sub-basin for RCP2.6 and RCP8.5, between June and September than outputs from the base data. The high change in ET mainly reflects the increase in temperature. Therefore, according to the RCP 2.6 and RCP8.5 climate forecasts, the temperature will increase more than in the RCP 4.5 forecasts. This is in line with the works of Musie et al. (2020) and Gadissa et al. (2019) in the Lake Ziway and CRV basins in Ethiopia, respectively. Musie et al. (2020) used the SWAT model to evaluate the impacts of regional climate variabilities and land use change on the water resources in the Lake Ziway basin. They found an increase in surface runoff and water yield due to the climate scenarios from the year 2000 to 2017. Gadisa et al. (2019) used projected climate scenarios to evaluate stream flows for the medium-term (2040 to 2070) periods for the RCP4.5 and RCP8.5 scenarios.

The results reported in Getnet et al. (2014), in the CRVB indicated that the hydrologic variations in water balance due to climate variability were highly significant (Getnet et al. 2014; Gadissa et al. 2019b; Musie et al. 2020a). However, in contrast to the study by Musie et al. (2020) (Musie et al. 2020a), the hydroclimate in our study was more predominant in WY than ET in the Ketar sub-basin. Another study conducted in the CRVB in 2007 on climate change impacts on water availability with a SWAT model indicating an increase of averaged annual rainfall from 2001 to 2099 can also be found (Zeray et al. 2007). However, Gadissa et al. (2019) projected a reduction in precipitation by 7.97 % and 2.55 % under RCP4.5 and RCP8.5 respectively for the future period from 2040 to 2070 (Gadissa et al. 2019b). Reduction in precipitation has strong correlation with reduction in water yield and surface runoff. Our study is thus in line with the findings of Gadissa et al. (2019) (Gadissa et al. 2019b) with minimal differences in the periods of occurrences. There are seasonal shifts in the pattern of occurrences of the components of the water balance when compared with the baseline data sets. These shifts are mainly from the changes in precipitation, temperature, and humidity patterns caused by greenhouse gases and other emissions.

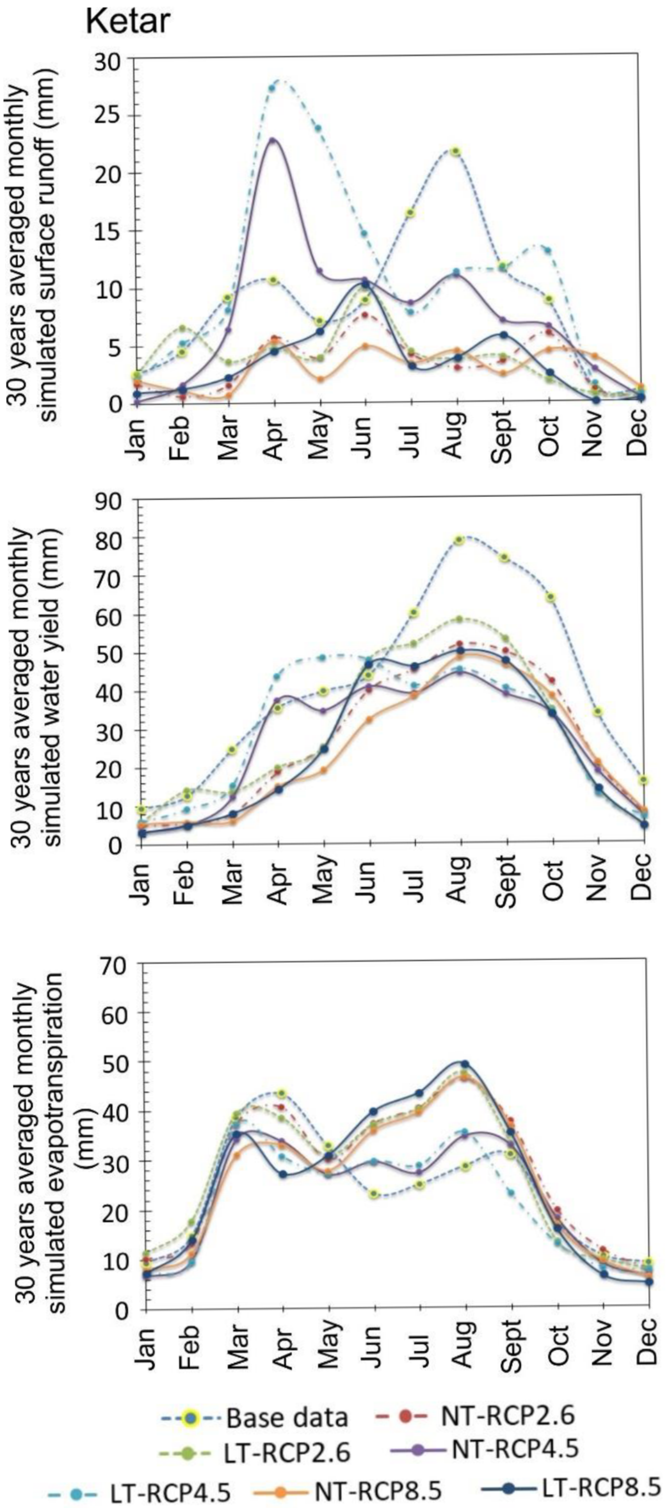


Fig. 9. The simulated monthly distributions of surface runoff, water yield and evapotranspiration in the Ketar sub-basin for the applied scenarios.

The monthly average changes in the water balance components for each of the scenarios in relation to the base year observed data simulations are presented in Fig. 12.
Based on the findings, agricultural water management in Ketar sub-basin – should, in future, focus on the time modification of farm operations, and on water harvesting to store excess water occurring in the unusual months. The WY is the major water balance component of the Ketar sub-basin in all the scenarios, and enhancement of the WY via afforestation, as ET is relatively low, together with conservation, will make the basin rich enough in water to curb the impacts of climate change. Besides, irrigation water supply scheduling based on the modified climate patterns is the recommended method of agricultural water management for the Ketar sub-basin.

The variation of the monthly average ET values due to climate change in the sub-basin is small in the near-term and long-term time periods of each of the RCPs. In Fig. 12, the changes in the monthly average ET values are almost insignificant in comparison with the other two water balance components throughout each of the RCP periods. This indicates that rainfall is the most important element among the climate factors in the sub-basin, and rainfall variability will have a tremendous impact on agricultural water management. The range of changes in ET in percentage terms is small over the basins in the near term and long-term periods of each of the RCPs, as indicated in Table 13.

6.3.2. Meki sub-basin

The Meki sub-basin is characterized by greater annual amounts of ET than in the Shalla and Ketar sub-basins. The annual surface runoff rises in all the RCP scenarios. There will be a seasonal shift of the peak runoff period from the usual July-to-September period to April-to-June in the sub-basin (Figure 10). In the long-term periods of RCP2.6 and RCP8.5, the runoff will increase greatly in relation to the baseline data simulation outputs. However, RCP4.5 will create a moderate range of changes in relation to RCP2.6 and RCP8.5. The change in annual average runoff varies from 6 % to 85 % in reference to the baseline outputs. The projected monthly distribution shows that this water balance component varies significantly over the months in both the NT and LT period.
The change in averaged annual WY ranges from −1.1 % to +23.9 % in relation to the baseline data simulated. The scenario analysis also showed a remarkable increment in the WY amount between May and October for all RCP outputs. ET is the major water balance component of the sub-basin (Figure 10). About 56 % of the rainfall on average turns into ET. This indicates that the sub-basin

water balance is highly sensitive to changes in temperature. Even though WY is good in the rainy seasons, most of it will be lost via ETs. Thus, for the Meki sub-basin, the impacts were more predominant in ET than in WY. This indicates the high seasonal weather variabilities in the sub-basin and its low hydroclimatic impact resilience. Similar findings were reported by Gadissa et al. (2019) and Musie et al. (2021) for this sub-basin. They used modeling approaches of RCM projections to assess the conditions of the Q, ET, and stream flows using the SWAT and WEAP models, respectively. In addition, Molla, (2014) has used physical assessment methods to indicate the sub-basin climate conditions (Molla 2014; Gadissa et al. 2018; Musie et al. 2021). These studies reported that the Meki sub-basin is the most hydroclimate-sensitive region. The strong weather variabilities in the sub-basin have resulted in wide ranges of changes in water resources similar to the findings of another study conducted by Getnet et al. (2014) in the CRVB (Legesse et al. 2003; Getnet et al. 2014; Gadissa et al. 2018). The annual variations in this study are also relatively large for the sub-basin (Table 13). The modeling results in this study for the sub-basin are thus inconsistent with the above study findings.

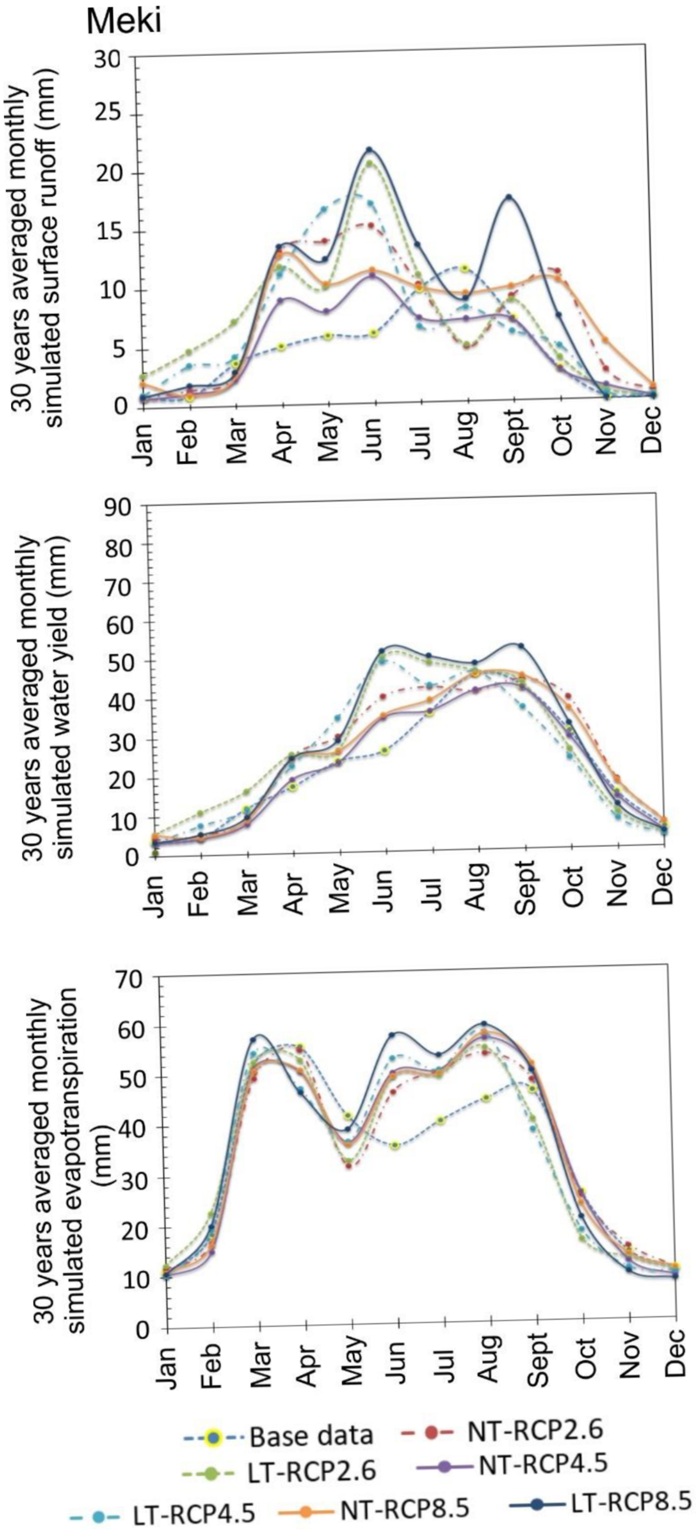


Fig. 10. The simulated monthly distributions of surface runoff, water yield and evapotranspiration in the Meki sub-basin for the applied scenarios.

High water losses through ET in the sub-basin should therefore be mitigated by water management interventions such as crop mulching, farm operations during minimum evaporation seasons, favoring minimum tillage to reduce soil evaporation, selecting crops that are more resistant to high levels of evaporation, favoring efficient irrigation water application, and introducing regular soil and water conservation practices to reduce the high seasonal runoff and ET. These findings are in correspondence with the outcomes of Volk et al. (2017) studies and recommendations (Volk et al. 2017). In Meki, water harvesting and storage during periods of flooding can also reduce water scarcity during peaks in demand. Flood management and protection infrastructures are also inevitable as there will be untimely and repeated flooding expected as per the analysis beyond the usual trend.

6.3.3. Shalla sub-basin

The response of this sub-basin to the analysis in the model indicates a stronger range of variations in its water balance components. However, the Shalla sub-basin has a lower annual runoff amount than the Ketar and Meki sub-basins (Figure 11). However, the changes in annual runoff vary between −21.9 % and +32.8 % from the baseline data simulation outputs. The average annual changes in WY vary from −10.1 % to +12.0 % because of the impacts. The changes in ET vary from +7.8 % to +15.1 %. The detail annual variations in percentage for each CSc and each component in each sub-basin are indicated in Table 13. ET increases significantly between June and September for all RCP projections. ET is the largest component, and most of the rainfall turns into ET. Because of the high ET and the small runoff, the entire sub-basin is characterized as a water-scarce region. The WY result for the Shalla sub-basin was moderate for all the CSc. Compared to other previous studies (for example Ayenew, 2007; Gadissa, et. al., 2018), Shalla has small WY output, but in the analyses conducted in this study, the sub-basin yielded a relatively higher amount. The difference could possibly be due to its complex hydrogeologic setting that needs to be verified in further studies. However, there is agreement on the fact that its surface water availability will be depleted due to the high ET and the low Q occurrences.

The water scarcity problem in this basin thus should be mitigated by improving water yield via yield enhancement approaches that also help to reduce evaporation loses. These include soil and water conservation to improve subsurface storage, crop selection and farm operation scheduling based on the new climate pattern. And minimum tillage to reduce soil evaporation, and the selection of ET-resistant crop varieties are cruicial. Investigated afforestation for controlling ET loses, and controled farm operations are also recommended. Furthermore, inter basin water transfers are recommended in adapting the impacts in the sub-basin.

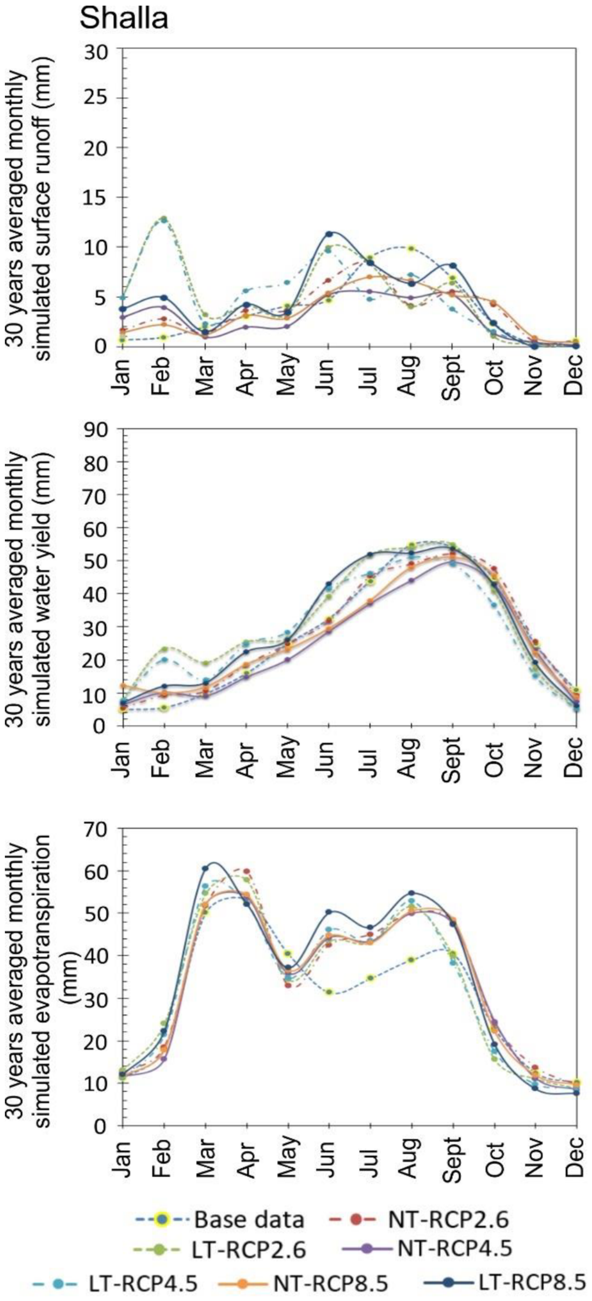


Fig. 11. The simulated monthly distributions of surface runoff, water yield and evapotranspiration in the Shalla sub-basins for the applied scenarios.

The projected monthly average values of each of the water balance components in each sub-basin with their respective baseline monthly average output values for each of the scenarios are presented in Figure 12. It indicates that the hydroclimatic impacts in the future in the CRVB are very high. The baseline data outputs are indicated with yellow rings around its graphs

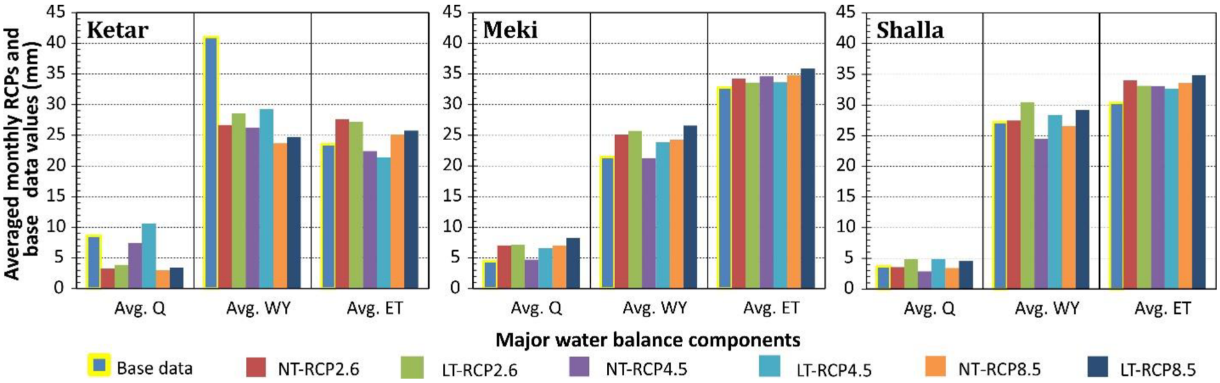


Fig. 12. Monthly averaged values of surface runoff (Q), water yield (WY) and ET in the sub-basins for different climate scenarios in relation to the baseline (1984-2010) outputs.

6.4. Discussion for climate change impacts

In the analyses, the climate variability and change has significantly affected the seasonal and spatial water balance settings both in quantity and in time of occurrences. A study conducted by Muluneh (2020) also found out that during the 2021- 2050 & 2066 - 2095 projection periods, in March to September, reference evapotranspiration (ETo) has increased by 5 % and 14 %, respectively in central rift valley region in Ethiopia. He also found a decrease in runoff & transpiration and an increase in evaporation (Muluneh 2020). In his finding Muluneh (2020) has indicated that:

- Changes in future climate are likely to have significant negative effects on the main water balance elements and on maize yield.
- In dry land areas of the Ethiopian CRV region, projected climate change will affect agricultural yield particularly maize negatively.
- Soil conservation practices such as tied ridges and soil fertility improvement will help to mitigate the negative impacts of climate change on maize.

Other studies also suggested that the use of improved fertilizer, altering planting dates based on the new climate pattern and supplementary irrigation can offset the negative impacts of climate change on food security in Africa and elsewhere (Ngigi 2009; Muluneh 2020; Gebrechorkos et al. 2020). Similarly, in a semi-arid Ethiopian rift valley region, a combination of late planting and low-to-medium fertilizer application offset the negative impacts of climate change on maize yield (Abera et al. 2018).

It was also concluded that terrain and the high climate variability of Ethiopia is emphasizing high various responses of current agricultural systems to climate change. These revealed that dedicated site-specific information and analyses are necessary for national and regional decision makers to respond with local relevance to a global exposure, in order to fight the food security challenges (Abera et al. 2018).

Musie et al. (2020) has evaluated the lake water level in central rift valley region and found out that the future agricultural developments without climate change scenario illustrated that the lake water system could cover more than 95 % of the future existing agricultural and domestic water demands. However, when climate change impact scenarios were accounted for, the coverage of irrigation in the basin reduces considerably from ~ 41 to ~ 78 %. They suggested demand management, supply improvement to increase lake level and reducing abstractions via efficient use of the water resources as a coping mechanism to climate change.

Uniyal et al. (2015) also showed that basin wide watershed and agricultural water management can improve the severe impacts of climate impacts on water resources in the watershed in his study region, India, and beyond.

A study conducted by Getnet et al. (2014) indicated that the increase in evapotranspiration because of climate change, has increased by +20 to +285 $\mathrm{Mm}^3\ \mathrm{yr}^{-1}$ in the periods from 2002 to 2009 in central rift valley basin that resulted for the high irrigation water demand. Therefore, integrated basin hydrology analyses for climate change scenarios, agricultural water use optimization and development planning are the mere solutions to offset the negative impacts of climate change on water resources.

Gadissa et al. (2019), in CRVB, using coefficient of elasticity method, estimated the values of streamflow change as – 26.9 % and – 15.8 % under RCP4.5 and RCP8.5 respectively in the mid-century. The streamflow change induced by anthropogenic factors can be associated with factors such as water abstraction, land use change, ground water abstraction, climate change and the other catchment properties (Gadissa et al. 2019c). Rift Valley basin water cycle components are highly sensitive to the impacts of future climatic change and therefore proper site-specific interventions of water resources management and development are recommended.

Moreover, it was indicated that expansion of irrigation has been taken as one of the climatic impact adaptation means in the central rift valley basin. As a result, the total irrigated area in the CRV has increased into around 12000 ha of land with water sources from Lake Ziway (31 %), Ketar River (27 %), groundwater (25 %), Meki River (11 %) and Bulbula River (4 %) and spring water (2 %). So, it is highlighted to improve the environmental and economic performance of current irrigated smallholders (Galata et al. 2021).

With climate change, Abraham et al. (2018), indicated that, annually projected decrement for precipitation has shown by 2.8 %, 7.5 % and 7.97 % for RCP 8.5 during 2020s, 2050s and 2080s respectively. However, for RCP 4.5 precipitations is projected to increase in amount by 2.69 % on 2020s and decrease by 2.7 %, and 1.6 % during 2050s and 2080s, respectively. However, seasonally maximum precipitation reduction is projected during the Ethiopian local rainy season of ‘Kiremt’ in all the model outputs (Abraham et al. 2018).

Therefore, the management of irrigation and related resources in the CRVB should strictly focus the local climate variability and its impact mitigation strategies according to the behavior of the hydroclimate impact on water resources and water resource management impacts on local climate.

7. Results and Discussion - Section B. Result for the impacts of LULC change

7.1. The past LULC changes

The changes in LULC in the past years were delineated in SWAT model and presented in Table 14. In the past, majority of the land in the CRV sub-basins were covered by agricultural land masses followed by range land, forest land, settlement, and water bodies in the order of their area coverages. Agricultural lands were observed to be increasing in all the sub-basins mostly at the expense of range land, and forest over the past time periods, Table 14.

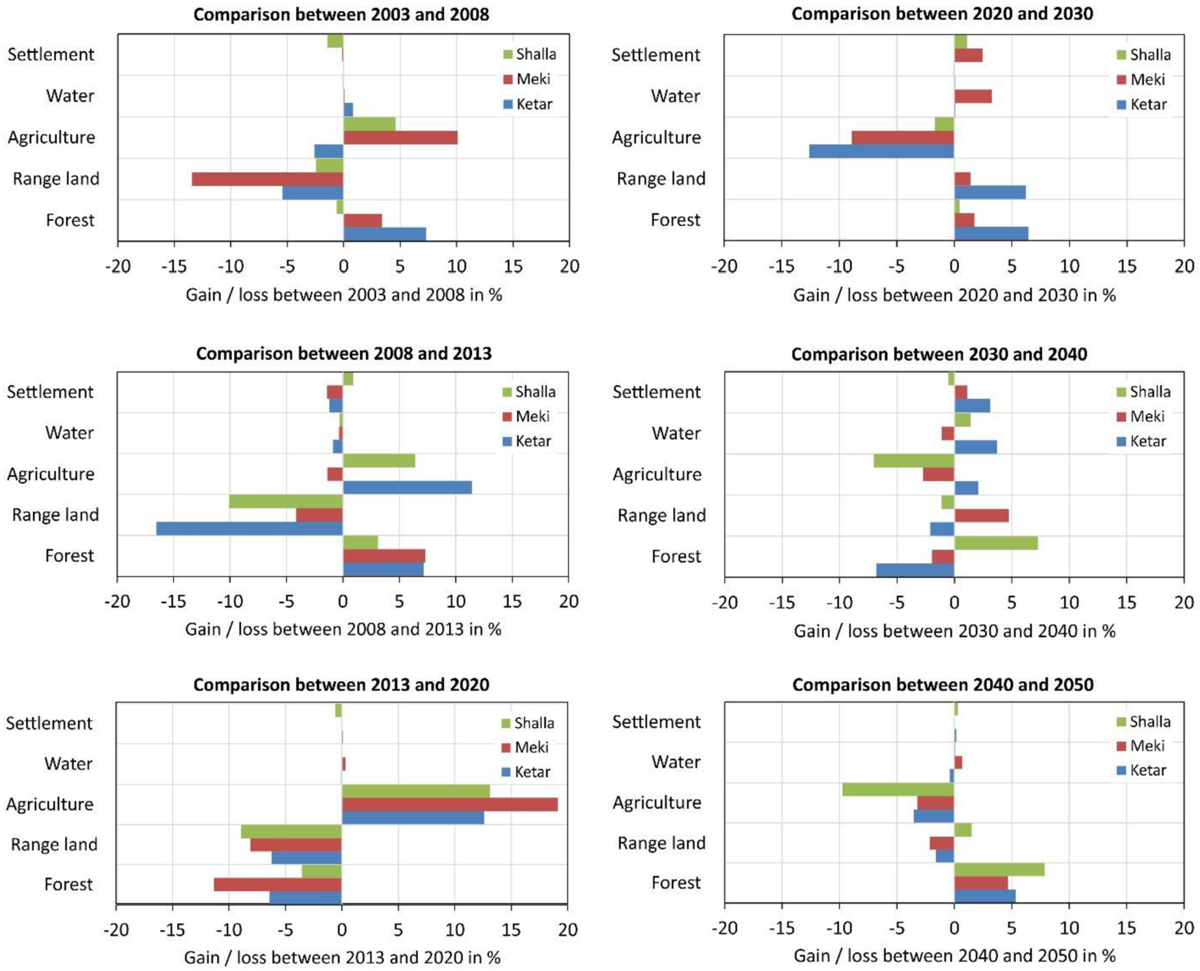
In the past years, the forest coverage was 3.77 % in 2003, 11.06 % in 2008 and 18.22 % in 2013 while it was 11.8 % in the year 2020 in the Ketar sub-basin. The change analyses indicate that in the past years the forest coverage was increasing in this sub-basin but in recent past, the coverage is going down in between the year 2013 to 2020 while agricultural area coverage was increasing from 74.39 % to 87.71 % in the time periods.

Almost all the range and bush lands in the sub-basins were changed to agriculture. It was about 28.39 % in 2003 and 0.21 % in 2020 in Ketar sub basin. It was also about 26.1% and goes down to 0.4 % in between 2003 to 2020 in Meki sub basin. Similarly, the coverage was reduced from 23 % to 1.55 % in Shalla sub-basin. See the details of the past land use change, and its coverages in the sub-basins, from Table 14.

The evaluation of spatial and temporal changes between various LULC classes during the years between 2003, 2008, 2013, and 2020 and for the predicted time periods 2030, 2040 and 2050 were analyzed and their results were shown in Fig.13. The percentage of gains and losses were done with LCM in its change analysis sub-section for the whole CRV maps. But to quantify the static coverage in each sub-basin for each land use category, SWAT HRU analysis tools were employed, and the results were presented in Table 14 for the past land uses and in Table 16 for the predicted land uses. Due to extreme agricultural practices, forest coverage was completely damaged in the year 2020 in Shalla sub-basin. Almost 98 % of the sub basin is covered by intensive agricultural practices. This severity also affects the water bodies to decline almost to zero in the year in the sub-basin. The downstream Shalla lake was also reported to decline in size. Similar trends were also observed in the change analyses of the other sub-basins, see Table 14. Therefore, afforestation and reforestation programs and basin wide land use planning and management interventions should be done in proper places in the sub-basins to conserve water and other natural resources.

Table 12. The past LULC area in percentage for each time step in the sub-basins.

Years	**Sub-basins**	**Total area in (ha)**	**Land use class cover in (%) out of the total area**				
			Forest	Range land	Agriculture	Water	Settlement
2003	Ketar	346,885.95	3.77	28.39	65.56	0.24	2.04
	Meki	193,582.58	7.01	26.10	63.98	0.88	2.03
	Shalla	146,625.82	1.06	23.00	73.61	0.41	1.92
`2008	Ketar	346,885.95	11.06	22.95	62.97	1.05	1.97
	Meki	193,582.58	10.41	12.67	74.07	0.95	1.89
	Shalla	146,625.82	0.43	20.56	78.22	0.32	0.46
2013	Ketar	346,885.95	18.22	6.43	74.39	0.18	0.77
	Meki	193,582.58	17.71	8.51	72.68	0.61	0.49
	Shalla	146,625.82	3.55	10.48	84.60	0.00	1.37
2020	Ketar	346,885.95	11.80	0.21	87.01	0.10	0.87
	Meki	193,582.58	6.37	0.40	91.84	0.94	0.45
	Shalla	146,625.82	0.00	1.55	97.68	0.00	0.77



Comparison between 2003 and 2008

Comparison between 2020 and 2030

Comparison between 2008 and 2013

Comparison between 2030 and 2040

Comparison between 2013 and 2020

Comparison between 2040 and 2050

Fig. 13. Percentage of area gains and loses of the past and predicted LULC categories between the time periods in the sub-basins as analyzed by LCM.

7.2. The predicted LULC analyses results and discussion.

Based on the probability matrix developed in LCM via Marcov-chain, the future land uses were predicted. The predicted LULC area coverages of the sub-basins were presented in Table 15. The LCM validation analyses indicate the results of its evaluation as hits, misses and as false alarms. The hits are the exactly predicted values from the three images cross tabulations. The misses are occasions where the model was unable to predict, but areas are changed, and false alarms are predicted as changed but do not changed in reality. Eventhough LCM does not incorporate the possible land use policy interventions in the future, the predicted land uses in the sub-basins valid good. The maps of the predicted LULC for the future periods were presented in Fig.14.

In the predicted scenarios, the changes in land use varies from sub-basin to sub-basin. For example, forest cover in the predicted years decreases from 18.24 % in 2030 to 16.78 % in 2050 in Ketar but it increases from 0.46 % to 15.61 % in Shalla sub-basin in between the years. In the general trend, coverage in agriculture and range land were predicted decreasing in between 2030 and 2050 while there will be increaments in 2040. The settlement area increases in Ketar and Meki sub-basins though it was predicted as decreasing in Shalla. The decrease in settlement in Shalla is not necessarly related to decrease in buildings but, dry land masses, and sandy areas which are categorized under settlement will supposed to be changed into agricultural areas and possibly to water bodies as the coverage of water bodies were also forecasted increasing.

Table 13. The predicted LULC area in percentage for each time step in the sub-basins.

Year	**Sub-basins**	**Total area in (ha)**	**Land use class cover in (%) out of the total area**				
			Forest	Range	Agriculture	Water	Settlement
2030	Ketar	346,885.95	18.24	6.40	74.40	0.18	0.78
	Meki	193,582.58	8.12	1.80	82.93	4.19	2.91
	Shalla	146,625.82	0.46	1.54	95.98	0.09	1.87
2040	Ketar	346,885.95	11.43	4.29	76.48	3.89	3.90
	Meki	193,582.58	6.16	6.52	80.21	3.07	4.00
	Shalla	146,625.82	7.74	0.41	88.97	1.49	1.33
2050	Ketar	346,885.95	16.78	2.69	72.95	3.49	4.08
	Meki	193,582.58	10.81	4.37	76.99	3.77	4.02
	Shalla	146,625.82	15.61	1.93	79.22	1.56	1.64

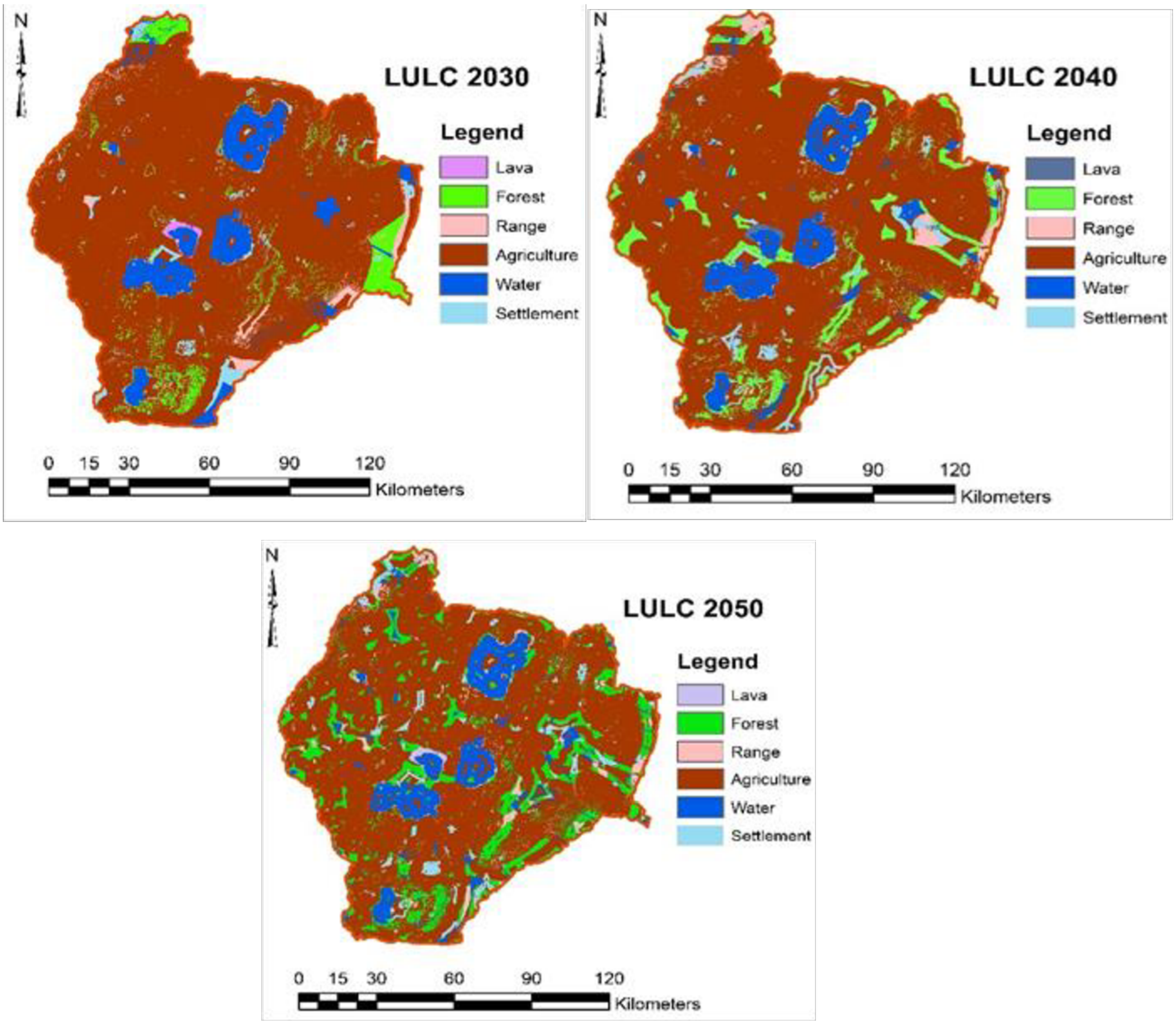


Fig. 14. The LULC maps for each of the predicted time steps.

7.3. Impacts of LULC change on the components of the water balance in the sub-basins

The hydrological impacts of the LULC changes were evaluated for annual, seasonal, and monthly distributions of the major water balance components such as surface runoff, water yield and evapotranspiration in the region. The analyses were done separately for each of the sub-basin to better understand site specific impacts. The climate factors were kept constant just to evaluate the sole impacts of the LULC changes in the time periods. Accordingly, the annual, seasonal, and monthly variations due to LULC changes in the Ketar, Meki and Shalla sub-basins were discussed separately. The base line climate data were employed for the scenarios and the base land use years which was in the base line data years (LULC 2003) was selected as a base year LULC for the comparison.

7.3.1. Ketar sub-basin

Surface runoff

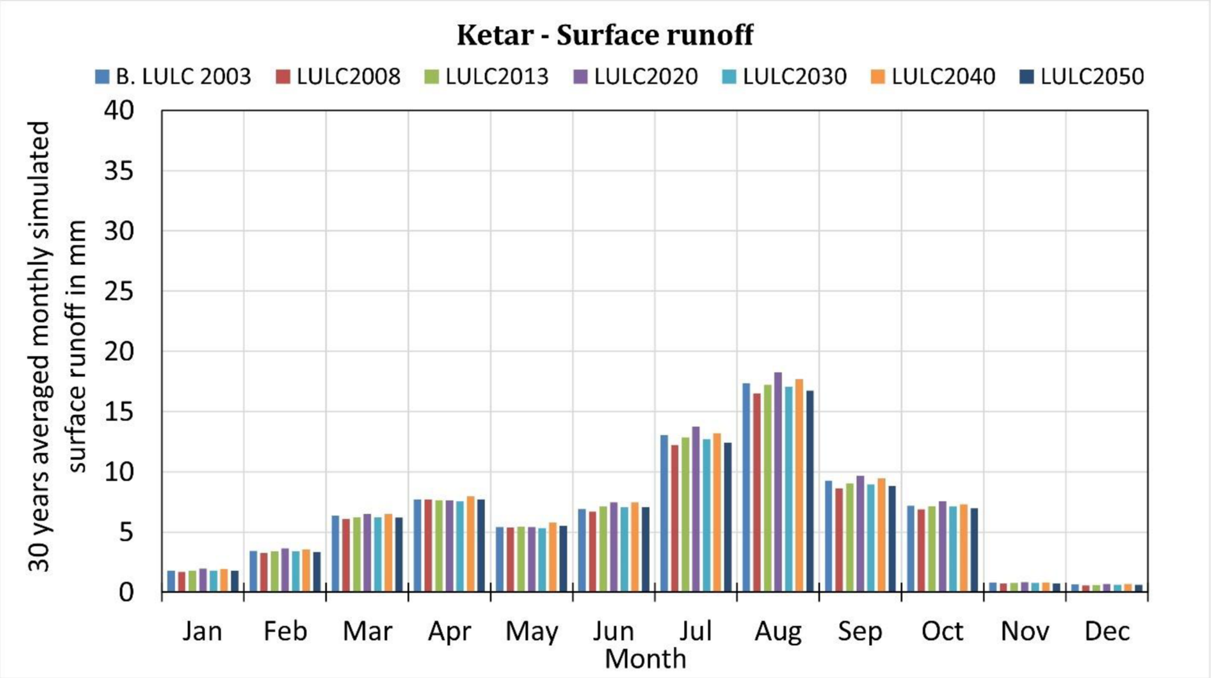
The change in surface runoff in this sub-basin varies on an annual average from -4.2 % to 4.2 % due to changes in land use over the time periods, 2003-2050, in relation to the base year land use (LULC 2003) simulated values. The highest reduction in runoff occurred in 2008 and the highest increment was in 2020. One of the reasons for surface runoff reduction was an increase in forest cover from 3.77 % to 11.06 % over the years from 2003 to 2008. Forest usually increases retention, interception, and consequently runoff will reduce significantly. The forest coverage was also associated with an increasing trend in 2013 but due to an increase in agriculture land and a reduction in range lands, the rate at which surface runoff occurs was increased until 2020. The runoff monthly distribution indicates that changes in land use have had huge impacts on surface runoff. The surface run off monthly distributions were presented in Fig. 15a. The zigzag line along the land use years in the figures indicated in Appendix E shows that the sole effects of the land use changes on runoff on monthly basis in the Ketar sub-basin is huge. The runoff and expansion in agricultural land and urban areas proved to have positive correlations. The result showed that an increase in agricultural land increases the rate of runoff in the area. Mostly, agricultural land increased in the basin at the expense of range land and forest cover, which are useful in retarding runoff enhancements.

Water yield

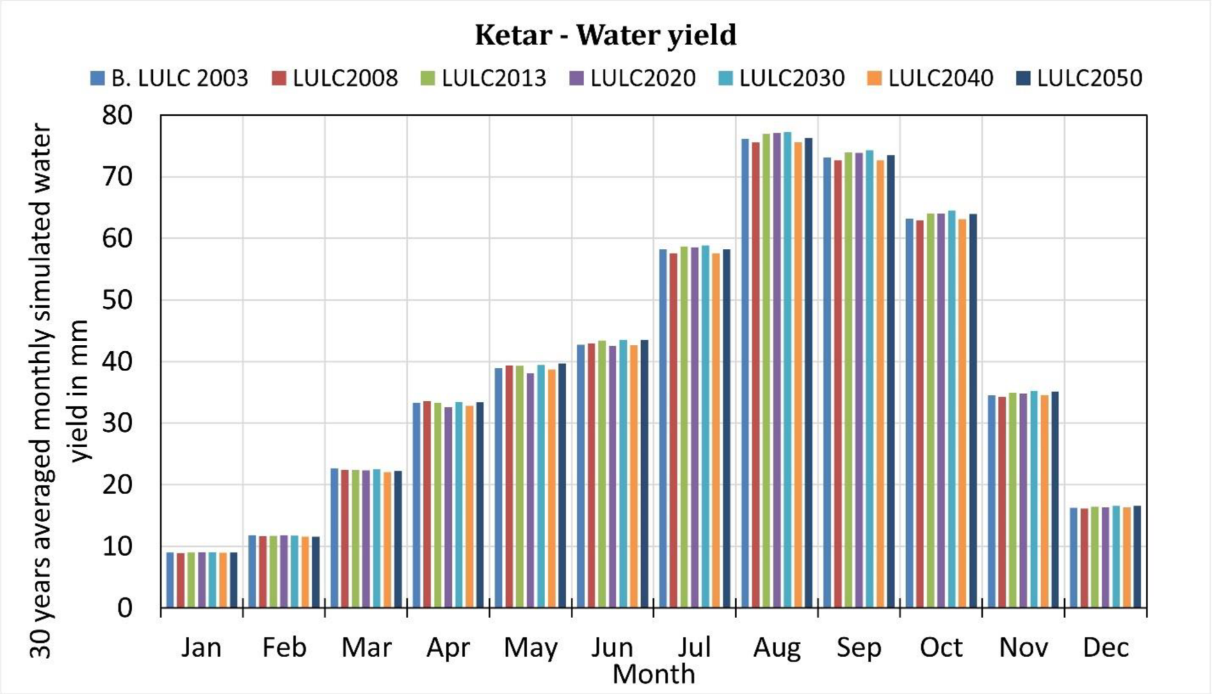
The annual change in water yield due to changes in land use on an average varies from -0.8 % to 1.53 % in the Ketar sub-basin over the past and predicted years. But the changes in quantity in the water yield in the sub-basin were varying from season to season even differs on monthly basis as indicated in Fig. 15b. Water yield is the major components of the water balance in this sub-basin in relation to the other major sub-components but the variation due to changes in land use in terms of its percentage is relatively small, Fig 15 d). However, huge volume of water is affected though it seems small in terms of its percentage out of the total water balance. For example, 1 % of the annual water yield in Ketar sub basin was 4.8mm, however, if multiplied by the total area of Ketar sub-basin will amount to more 16 Mm^3 of water which is very huge. Land use change management will therefore have a vital role in improving the availability of water in the sub-basin.

Evapotranspiration

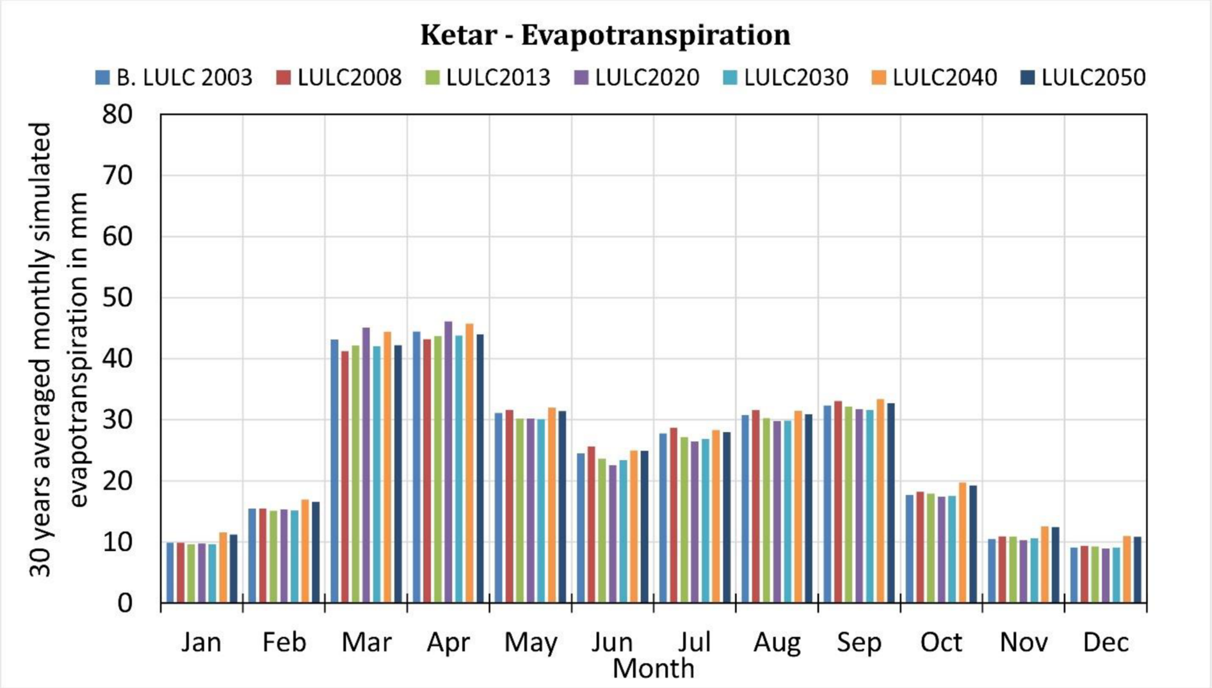
Like the other two major water balance components, ET also shows strong variations along with changes in land use and its monthly distributions are also varying as indicated in Fig. 15 c). For instance, the ET varies on annual average from -2.08 % to 5.36 % due to changes in land use from the base land use year simulation outputs over the analysis's periods, from 2003 to 2050. Thus, ET has a strong correlation with land use and land cover changes in this sub-basin. Therefore, land cover management will help its water resources improve in terms of its availability or in protecting losses through evapotranspiration.



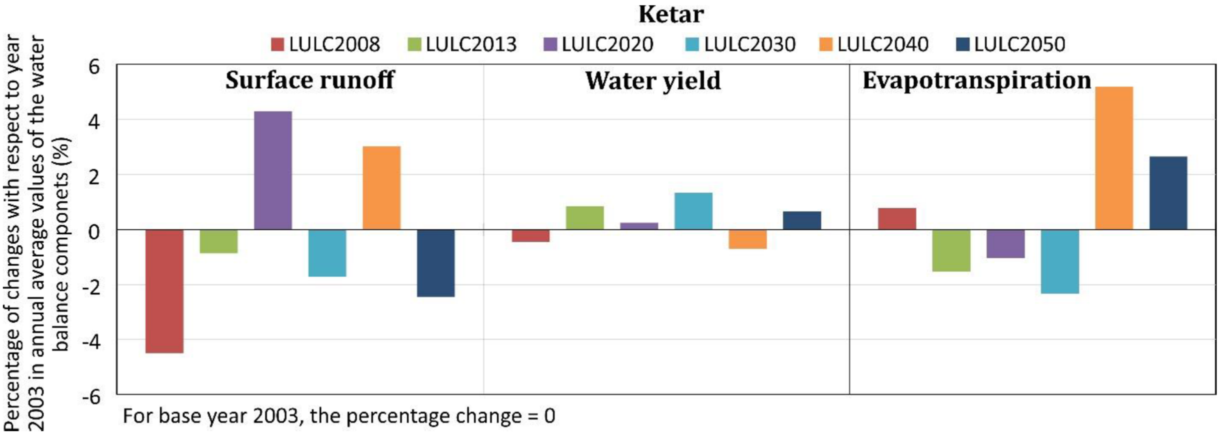
a) Surface runoff



b) Water yield



c) Evapotranspiration



d) Annual percentage of changes in the major components of the water balance

Fig. 15 a), b), c) & d). Averaged monthly distributions of the components in the Ketar sub-basin and annual percentage of changes due to changes in LULC.

The variability in ET and runoff were stronger than the variability in water yield as indicated in Fig.15 d as percentage of change. Therefore, surface runoff and ET are highly affected by changes in land use and land cover. This is highly related to changes in forest cover in the sub-basin and thus forest cover is the critical element of the LULC in the sub-basin. Its improvement will therefore favor water resource availabilities.

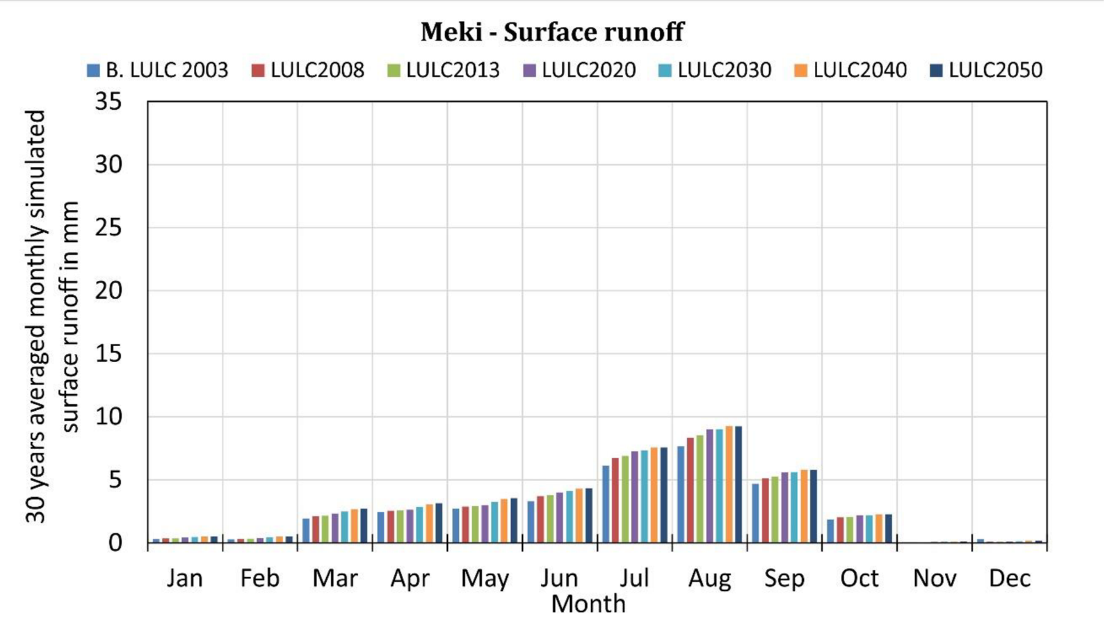
7.3.2. Meki sub-basin

Surface runoff

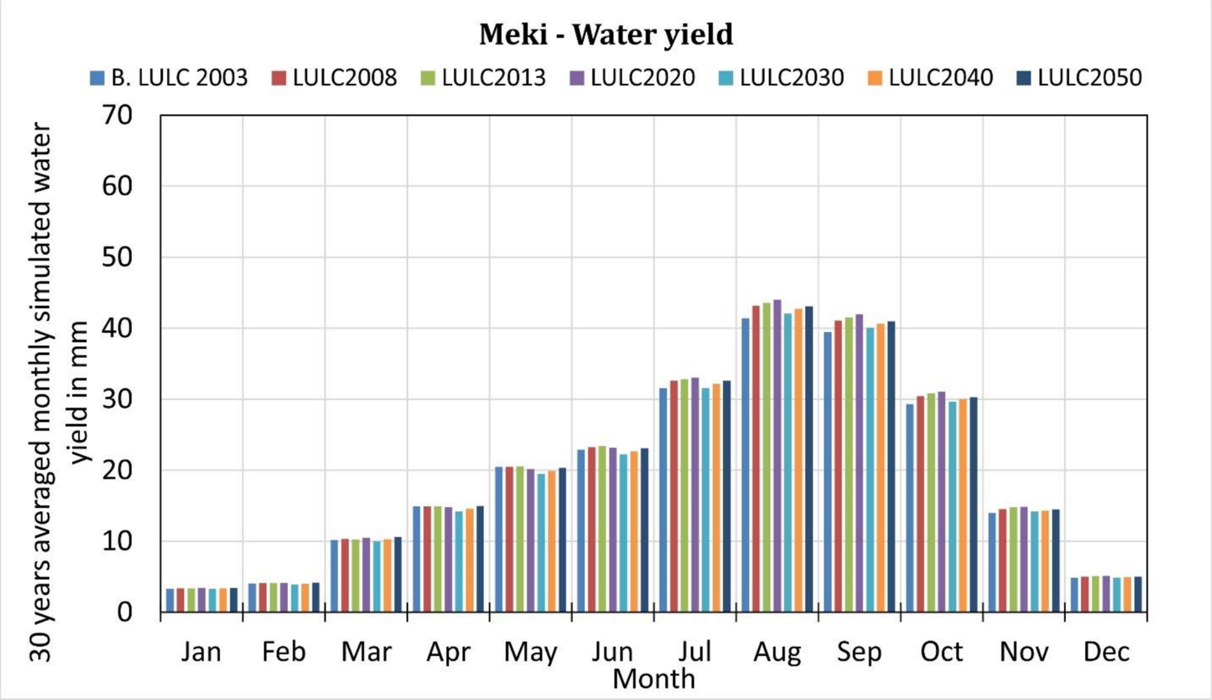
The analyses in the model indicated that the monthly average variation in surface runoff (Q) in Meki sub-basin is from -1.15 % to 25.37 % for the years from 2003 to 2050. The annual sum of surface runoff was 34 mm in 2003 while it was 36.97 mm per unit area in the year 2020, see Appendix F. These changes were mainly due to the changes in LULC in the sub-basin as others such as climatic and management factors were kept constant in the model. In the predicted LULC scenarios, the annual surface runoff in the sub-basin will rise to 39.88 mm per unit area in the year 2050. This indicates that huge amount of water will become additional runoff in the coming 30 years in the sub-basin, which is almost about 5.88 mm per unit area due to the predicted LULC changes. This observation is similar to the works of Musie et al. 2020, which indicates that land use change scenarios in their analysis in the sub-basin has also shown an increment in surface runoff in the future (Musie et al. 2020a). Therefore, water harvesting to store the runoff in excess in the future in the sub-basin is very crucial to improve the water availability index of the sub-basin to use during peaks in demand.

Water yield

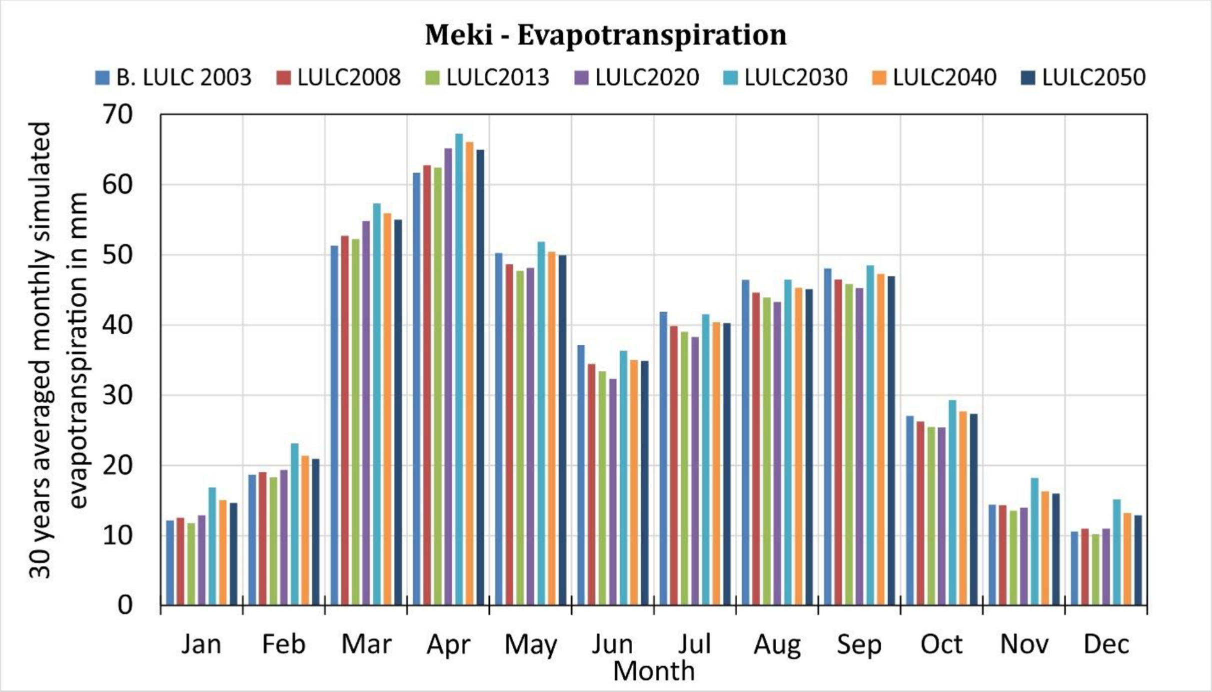
The variability in water yields due to the sole impacts of land use change on an average range from -0.93 % to 3.27 % in this sub-basin. Water yield (WY) is the second most abundant water balance component in Meki sub-basin. The simulated water yield monthly average value ranges from 19.62 mm to 20.51 mm per unit area due to change in land use as can be seen from Appendix F. These variabilities in water yield due to the LULC dynamics will have their own effect on water use planning and management in the sub-basin. Water yield enhancement strategies based on water balance sensitivities to changes in LULC are quite essential.



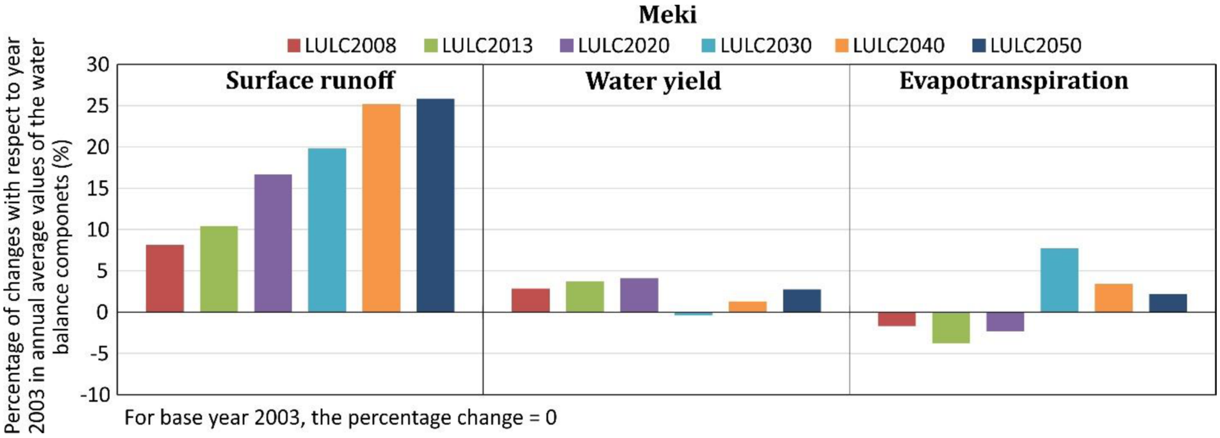
a) Surface runoff



b) Water yield



c) Evapotranspiration



d) Annual percentage of changes in the major components of the water balance

Fig. 16 a), b), c) & d). Averaged monthly distributions of the components in the Meki sub-basin and annual percentage of changes due to changes in LULC.

Evapotranspiration

ET was the major component and has shown an average variation from -4.43 % to 8.39 % from the base land use year simulation outputs in monthly averaged ET output values, see Fig 16 d). The lowest annual ET was recorded in the year 2013 in this sub-basin. In the year 2013, forest coverage was high but due to significant reduction in open water bodies in the sub-basin from an area coverage of 0.95 % to 0.61 %, as indicated in Table 14, reduction in ET was observed. This reduction in area coverage of water bodies has reduced ET significantly and surpasses the rate of ET increments from forest area increments as evaporation from open water bodies are obviously high and the net balance indicated reduction in ET in the time periods. These all are the sole impacts of changes in LULC in the sub-basin and thus investigated land use planning according to water balance sensitivities to its changes will help improvement in water availability.

7.3.3. Shalla sub-basin

Surface runoff

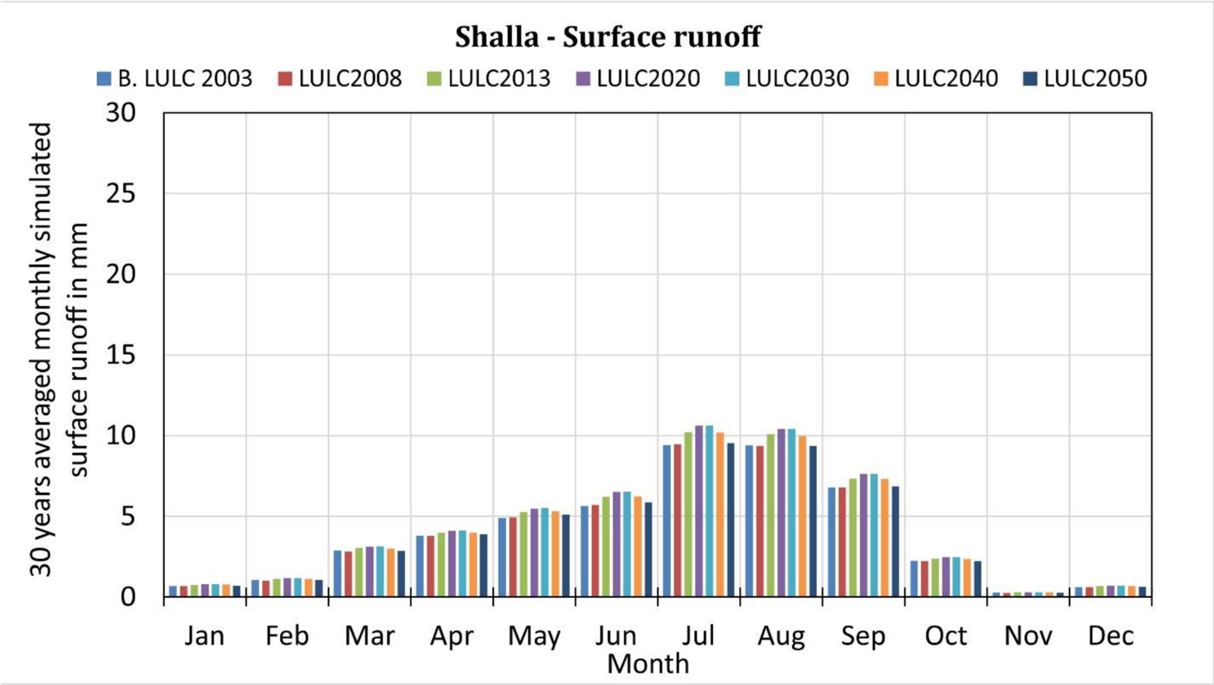
Like the other sub-basins, LULC change has created a significant impact on surface runoff component in the Shalla sub-basin. The annual average simulated surface runoff varies from -20 % to 32.07 % from the base land use annual average simulated values. The surface runoff was smaller in amount in relation to its water yield and ETs as observed from Fig. 17 a). In this sub-basin the surface runoff annual sum ranges from 47.61 mm to 53.44 mm per unit area for different land use years. The total average surface runoff is about 6.67 % of the total annual rainfall in the sub-basin, which is a relatively small amount. However, the amounts are on an increasing trend in all the sub-basins as indicated in figure 17 a), b) c) & d). the monthly distributions are given in Appendix G. In the periods, the changes in LULC were mainly from range land to agriculture and these have affected the runoff conditions of the sub-basin significantly.

Water yield

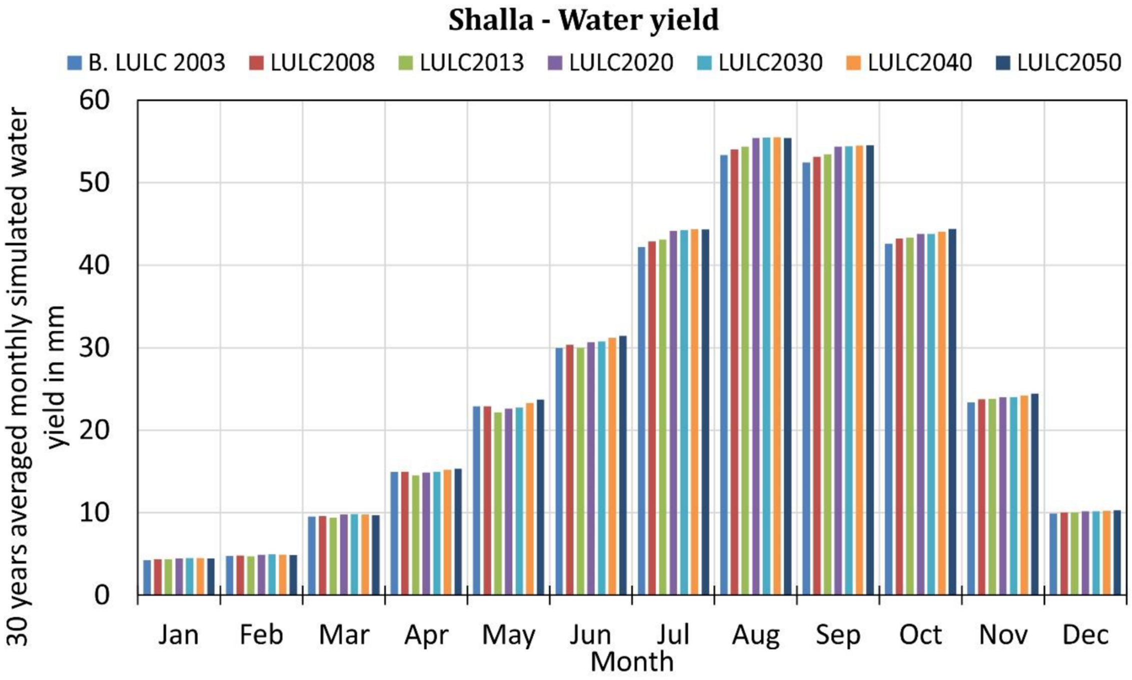
Naturally, water yield is a catchment water production capability which is highly related to land use and land cover conditions. In the Shalla sub-basin, water yield monthly distribution was varying significantly. And the annual average variation in water yield from the base year annual average ranges from -10.38 % to 13.49 %. As evapotranspiration is higher and afforestation alone may not improve the generation capacity of the sub-basin and therefore investigated intervention of basin management to improve catchment water yield is crucial. Application of integrated water resource management that incorporates all possible management factors will benefit its improvement.

Evapotranspiration

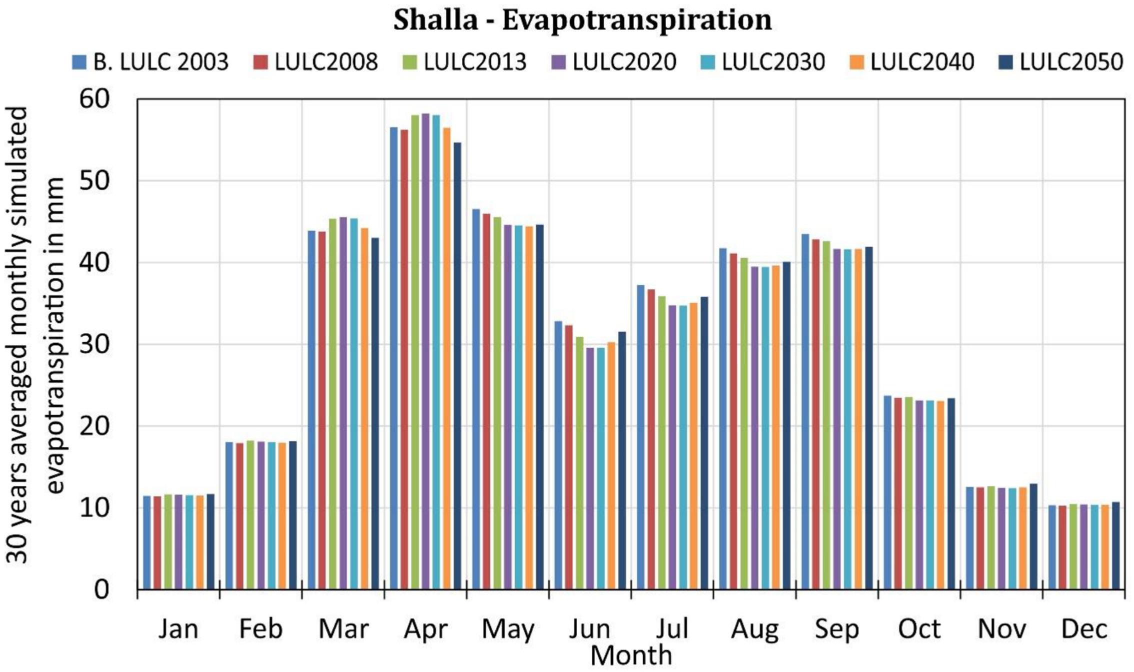
It is the major component of the water balance in the sub-basin. In all the land use years, the simulated ET annual average values were increasing in relation to the base land use years. The cause for the increment is due to the combined change effects of LULC categories in the predicted years. Therefore, overall catchment management and integrated land use planning will improve the water resource availability of the sub-basin and reduction in evaporation loses.



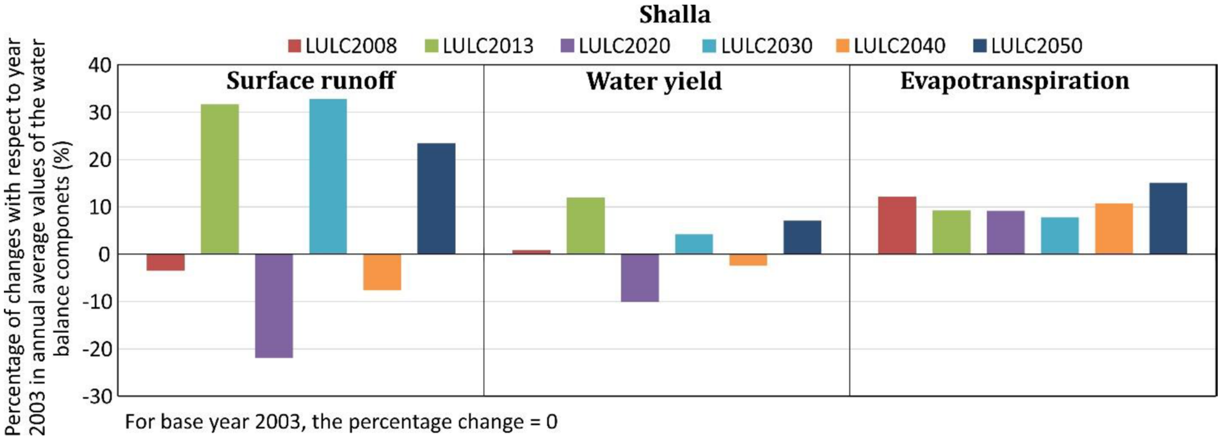
a) Surface runoff



b) Water yield



c) Evapotranspiration

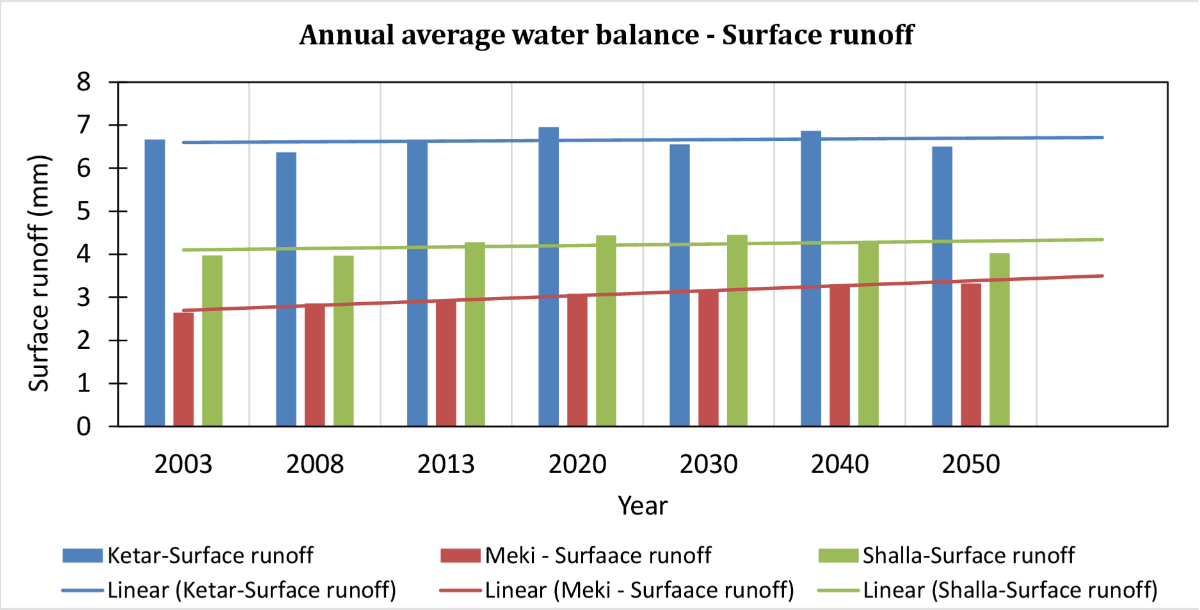


d) Annual percentage of changes in the major components of the water balance

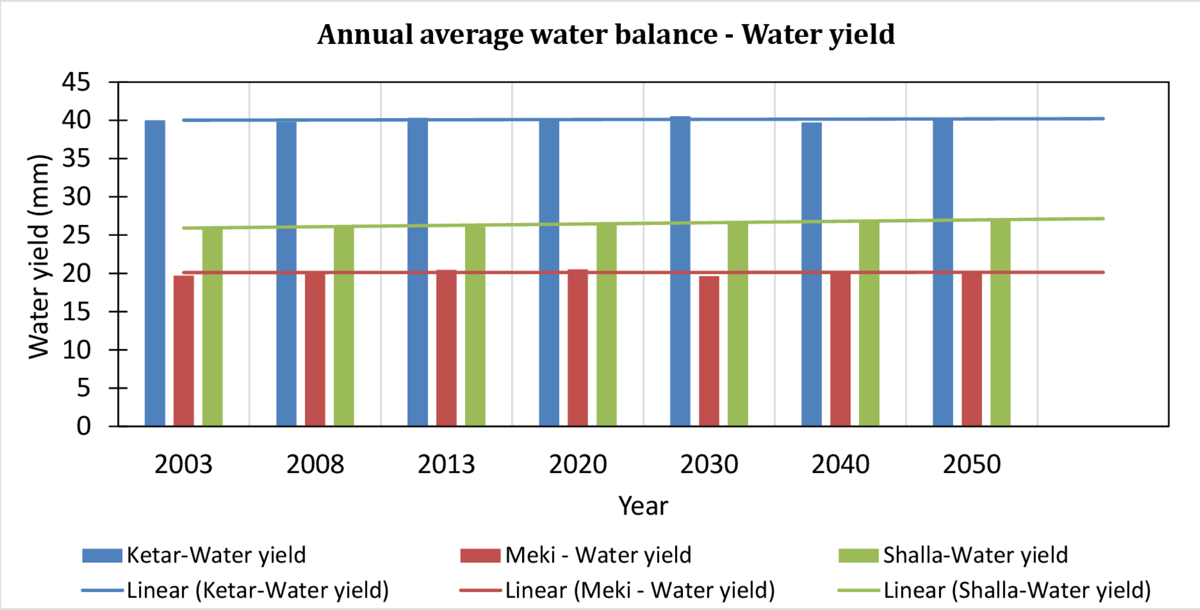
Fig. 17 a), b), c) & d). Averaged monthly distributions of the components in the Shalla sub-basin and annual percentage of changes due to changes in LULC.

7.4. The overall water balance trend

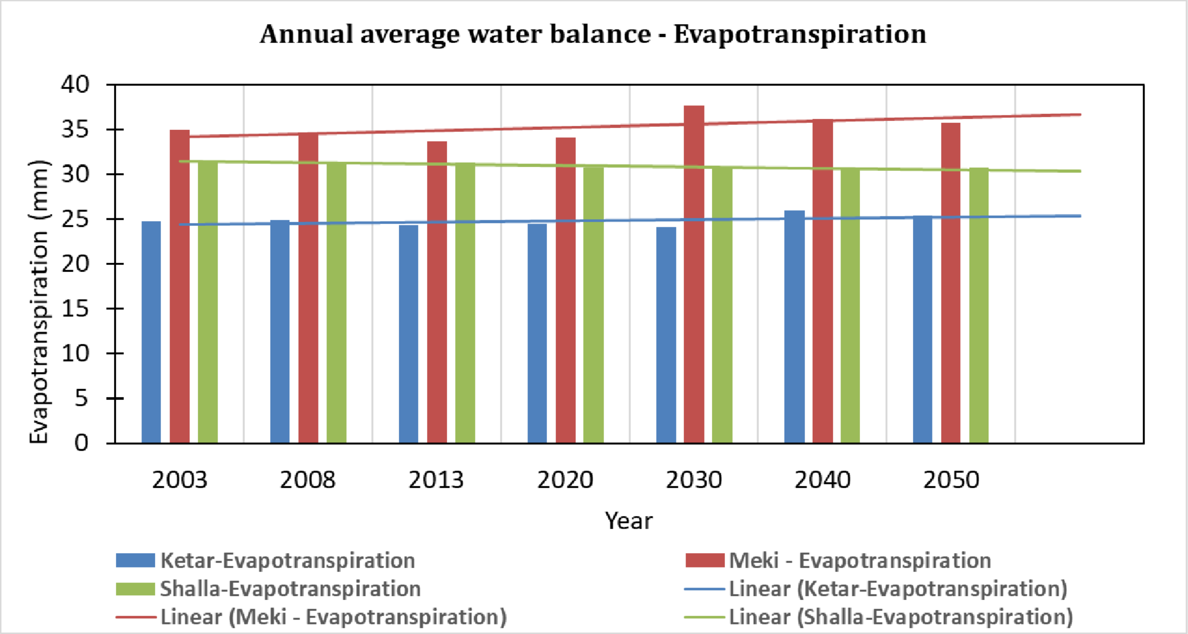
The general trend in major water balance components in the sub-basins are indicated in Fig 18 a), b) & c). The increase in surface run off and in evapotranspiration are more significant in the sub-basins. The change in annual water yield is not high and it seems decreasing in the Meki sub-basin. Due to changes in LULC in the sub-basins thus reduction in water yield components which are the crucial component for water availability are the critical part that needs to be addressed. Water yield enhancement and investigated land use management to improve water yield is thus necessary.



a) Surface runoff



b) Water yield



c) Evapotranspiration

Fig. 18 a), b) & c). Annual average values of major water balance components and their trends in the sub-basins due to changes in LULC in relation to base year land uses.

7.5. Discussion for LULC change

The magnitude of land use change to emissions of GHGs is well understood. Approximately one-third of anthropogenic CO_2 emissions since 1850 attributed to land use activities (Stone 2009). Nevertheless, these days, alterations in surface fluxes of moisture and energy resulting from land use activities holds more direct implications for regional scale climate phenomena than associated changes in emissions (Stone 2009).

Therefore, land use change management will have a significant role in mitigating the local climate change impacts. Understanding the local changes of land uses and its impacts on water fluxes and on freshwater cycle of the locality is of paramount importance. It helps in searching for possible land use management to enhance the mitigation of its impacts and the impacts of climate change particularly on water resources. It is therefore very imperative to develop land use model that favors to develop land management policy that can promote future land use transitions capable of meeting multiple goals and satisfying demands from various stakeholders by incorporating a broad spectrum of disciplines and that sustains local weather impacts and that downs the greenhouse gas emissions (Long & Qu 2018).

Accordingly, the high land use and land cover dynamics in CRVB should be properly understood and managed in a manner that the components of the water balance status quo are amplified. This will help to conserve the water resources in the locality and to mitigate the impacts of local climate changes.

Other study in the region also indicated significant changes in land use and land cover and recommends land use change management to protect the sedimentation of water bodies in the lower reaches (Desta & Fetene 2020). They indicated that cultivation, agroforestry, and human settlement are expanding in the region from 1973 to 2018. They recommended awareness raising and provision of technical training about conservation interventions to communities in the watershed that provides information for corrective measures to protect further degradation and irreversible losses that might happen to the biotic and abiotic resources in the Lake Ziway watershed.

The driving forces for the land use changes in the region are categorized into proximate (direct) and underlying (indirect) effects. The direct driving forces include LULC changes driven by local people to produce food crops and to meet fuelwood and charcoal demands (Desta & Fetene 2020).

Demographic pressure, poverty, land use policy and topographic effects are the indirect driving forces for land use and land cover changes in CRVB according to Desta and Fetene (2020).

LULC changes can affect surface runoff, recharge of groundwater and water quality in a watershed (Desta et al. 2015; Desta & Fetene 2020). The expansion of cultivated lands at the expense of forests might lead to falling groundwater levels and degrading other natural vegetation (Garza-Díaz et al. 2019). Thus, local climatic conditions and the hydrological regime could be affected by LULC changes in the Lake Ziway watershed in similar manner. These changes may also contribute to the problem of global warming by releasing the greenhouse gases (CO_2) into the atmosphere (Elias et al. 2019). Proper land use policy and land use change management is thus very crucial for protection and conservation of water resources as well as for mitigation of local impacts of climate change.

8. Water, irrigation, land use and climate nexus approach

Review recommendations for management options

8.1. Climate change adaptations, irrigation, and related resources management options

Climate change impact adaptation strategies nowadays changed their attentions on searching solutions more than understanding the problems and to their implementation than planning (Chen et al. 2019). These impacts are growing multifaceted and complex and thus the implementation strategies are more likely linked to multi-sectoral applications. Some climate change adaptation strategies consist of many factors such as altering crop composition, irrigation management and changing land uses, which show the potential to increase the resilience of agricultural systems to future impacts of climate change (Chen et al. 2019). Smarter adaptation action strategies are very crucial for effective management of the impacts. These adaptation actions must be informed with robust data and assessment tools that can be easily accessible to all. To implement faster adaptation strategies that can improve the gap between planning and implementation, systematic adaptation strategies that incorporate local level and all vulnerable communities as well as ones that improve the frontiers of knowledge on impact adaptations must be considered (Belay et al. 2017; Chen et al. 2019). The adaptation strategies should be systematic, cost effective and should also be ecofriendly. Therefore, integrated planning and use of water-land-agriculture and climate nexus synergies in irrigation management will bring big and sustainable results.

These integrated nexus development approach of irrigation with climate and land use change as well as with socio economic factors will enhance sustainable and high performance of irrigation development (Amede 2015; Belay et al. 2017; Eshete et al. 2020). Despite significant efforts by government and other stakeholders to improve agricultural water management for enhancing irrigation, different constraints related to policy, institution, capacity, infrastructure, and the market still exist in Ethiopia (Haile & Kasa 2015; Eshete et al. 2020). Even though many recent reviews were conducted on various aspects of irrigation in Ethiopia (e.g., Haile & Kasa 2015; Gebrehiwot 2018), none brings together the diverse aspects of challenges, advancement, and opportunities concerning improving water use efficiency in irrigation in the country. Despite significant efforts by government and other stakeholders to improve agricultural water management for enhancing irrigation, different constraints related to policy, institution, capacity, infrastructure, and the market still exist in Ethiopia (Haile & Kasa 2015; Eshete et al. 2020). Even though many recent reviews were conducted on various aspects of irrigation in Ethiopia (e.g., Haile & Kasa 2015; Gebrehiwot 2018), none brings together the diverse aspects of challenges, advancement, and opportunities concerning improving water use efficiency in irrigation in the country.

The nexus synergies of water-agriculture-land use and climate are therefore to put together issues related to advancements, challenges, and available opportunities for improving irrigation water use efficiency and highlight possible practical management applications in Ethiopia particularly in CRVB. To achieve successes in synergies for water-irrigation-land use and climate, proper tools, and methodologies in its implementation and for its sustainable use are necessary. For instance, Eshete et al. (2020) indicated in their critical review on irrigation management in Ethiopia that in the future, increased use of remote sensing techniques, more versatile sensors, simulation, and quantitative models are likely to be seen to improve water use efficiency in irrigation (Eshete et al. 2020). Due to the efficient use of the technologies, the spare water saved is being used to expand more areas in irrigation, which results in an increased income for the household (Ibid). They also recommend water savings, water-efficient technologies and practices that need to be used in combination with other measures such as incentives for land use management and its conservation works to sustain the environment and irrigation management (Ibid)To achieve successes in synergies for water-irrigation-land use and climate, proper tools, and methodologies in its implementation and for its sustainable use are necessary. For instance, Eshete et al. (2020) indicated in their critical review on irrigation management in Ethiopia that in the future, increased use of remote sensing techniques, more versatile sensors, simulation, and quantitative models are likely to be seen to improve water use efficiency in irrigation (Eshete et al. 2020). Due to the efficient use of the technologies, the spare water saved is being used to expand more areas in irrigation, which results in an increased income for the household (Ibid). They also recommend water savings, water-efficient technologies and practices that need to be used in combination with other measures such as incentives for land use management and its conservation works to sustain the environment and irrigation management (Ibid).

The impacts of climate change especially on agricultural sector in sub-Saharan region are manifested as high evaporation loses of water from irrigated farms that occur from poor water management resulted from lack of infrastructures and proper management integrations

(Awulachew 2019). Evaporation loss is the critical element affecting irrigation management in the region including CRVB in Ethiopia. Integrated applications of methodologies and technologies together with environmental management in synergy were recommended for adapting the impacts of climate change in those irrigated farms (Awulachew 2019).

8.1.1. Measures recommended to improve soil evaporation loses in irrigated farms

Irrigation application/efficiency improvement

In the country, farmers' water application practice can be considered as poor and susceptible to huge water loss and undesirable environmental impacts (Ulsido et al. 2013). Improving water productivity and water usage efficiency should be given priority in dry areas to sustain agricultural production and it may be achieved through land levelling, drainage, and improved irrigation methods. Cai et al. (2003), suggested that efficiency at the river basin level can be improved by (1) increasing output per unit of evaporated water, (2) reducing losses of usable water to sinks, (3) reducing water pollution, and (4) reallocating water from lower valued to higher valued uses (Cai et al. 2003). Batchelor (1999), also suggest several ways to improve physical and economic efficiency at the farm level:

- Agronomic (for example, improving crop husbandry and cropping strategies).

- Technical (for example, installing an advanced irrigation system).

- Managerial (for example, adopting demand-based irrigation scheduling systems and better maintaining equipment); and

- Institutional (for example, introducing water pricing and improving the legal environment) (Batchelor 1999).

Other soil in situ, agronomic and conservation measures such as deficit application on irrigated farms especially on small scale family based irrigated farms can play tremendous impact in improving family irrigation productivity and family food and water securities. For instance, improvement of application infrastructures, such as family drip system has improved the water loses through evaporation, improved family garden productivity and largely supported the food consumption of many families in semi dry regions of Ethiopia and backs up the need of local market in the surrounding towns for fresh vegetables even in the drought years (Biazin et al. 2012). Drip irrigation reduces evaporation and deep percolation, controls soil water content more precisely and eliminates the effects of wind. Also, drip irrigation solves practical irrigation problems created by hilly terrain, or texturally non-uniform fields. It also allows flat culture farming system which helps save labor and operating costs of making furrows and ridges (Biazin et al. 2012).

Irrigation scheduling

Proper irrigation scheduling based on site specific soil, climatic and social factors should be adopted to improve the effectiveness of irrigated farms. Improving WUE is complex, embracing not only agronomic issues, but also hydro-geological, human, economic and social issues (Jones 2004). Supplying enough water to the farm or to the crop alone should not be the end goal of irrigation, the right application timing and period based on site specific climatic, soil, crop and social conditions is very crucial for water savings. To secure highest crop production with the least water use, it is necessary to know the water requirement of the crop and once its water requirement is known, appropriate irrigation scheduling can be designed, which can lead to improvements in the yield, income, and water saving. For instance, generally, it is not advisable to irrigate farms in sunny, mid-day and windy periods in tropical climate regions. In these periods, evaporation is by far higher than the root up takes and sometimes beyond the infiltration rates. Soil temperature is also another factor that enhances soil evaporation (Busari et al. 2015). Therefore, Irrigation scheduling technical support i.e., better extension services during irrigation management to the farmers in the tropical savanna region including Ethiopia's CRVB will play a great role to curb the water loses and in improving water productivities. The impact of evaporation is one of the major challenges of irrigation water management effectiveness and needs to be solved if irrigation development is required to meet its goal.

Water saving during excess periods (to minimize temporal scarcity)

Globally, the total volumes of water stored within the soil are huge, but at any given locality they are relatively small and quickly depleted through evapotranspiration. Because of this, in recent decades there has been increased interest in various in-situ rainwater management techniques that enhance infiltration and water retention in the soil profile (Awulachewu 2019). The high rainfall variability in the country both in space and time has resulted in water scarcity during peak irrigation periods and makes irrigation water management unattractive and center of conflicts that leads to crop failure and other social damages in the river system. Ex-situ water storage facilities can help in addressing water scarcities occurring due to climate variability, erratic rainfall and high evaporation loses (Dile et al. 2013). The government of Ethiopia is trying to create farmer awareness to have water banks at household level to curb the rainfall variability or to bridge dry spells through supplemental irrigation of rain fed crops in smallholder farming systems to improve the lives of rural people at low cost and with minimal outside inputs. This could be achieved with water harvesting system, which involves collecting runoff in small storage structures (Awulachew et al. 2005). Water harvesting is suggested as a key option for a sustainable water management strategy to increase agricultural production while balancing the effect on the environment (Dile et al. 2013). Water harvesting can play a bigger role in achieving water productivity. Water harvesting practices are classified into three categories: macro-catchment systems, micro-catchments, and in situ systems (Ngigi 2003). Macro-catchment water harvestings are also called external water harvesting systems or ex situ systems (Biazin et al. 2012; Ngigi 2003). These systems collect water from a large area and have water collection catchment, conveyance, and storage structures. Micro-catchment water harvesting systems collect water from a relatively small catchment area (Biazin et al. 2012). Large irrigation systems sometimes cannot always supply water at the right time. Storing water in the farm ponds can help farmers to irrigate their farm when they need it especially when the rate of evaporation is assumed to be lower (Awulachew et al. 2005). It is also important to note that Rainwater Harvesting (RWH) can be used to rehabilitate degraded land and retain moisture. Thus, water storage structures can improve irrigation water management and the country's water storage capacity to facilitate better production.

Improving water use efficiency via technologies

Water use efficiencies (WUE) improvement can also be supported by low-cost irrigation technologies and farmers motivation. To improve water use efficiency and reduce the risk of over-watering, the agricultural irrigation system can be improved. The potential merits of affordable micro-irrigation technologies like low-pressure drip kits, treadle pumps, small diesel pumps, water conservation practices, small basins, pits, and runoff-based system are increasingly recognized by the government and other stake holders in the country for improving irrigation efficiencies (Eshete et al. 2020).

Eshete et al. (2020), in their study indicated the importance of remote sensing for water use efficiency improvement. They indicated that WUE in any area is achieved by making the timing and quantity of irrigation applications optimum. Since the conventional methods are expensive, time- consuming, and site-specific and cannot be easily automated, remote sensing can be applied for measurement, monitoring, and reporting of water use and management (Eshete et al. 2020).

Hence remote sensing in Ethiopia helps irrigators know the ET rate and apply the right amount of water at the right time to ensure that the crop is not stressed.

The development of cost-effective technologies such as sensors can improve water-use management by allowing for more precise monitoring of soil moisture content at high degrees. Therefore, the integration of crop water requirement (agronomic), soil moisture content (soil and water relationship) and evapotranspiration quantification (climate analysis) in synergy for irrigation water use efficiency improvement with the help of remote sensors and from satellite networks will easy the application. These will bring dramatical improvement in irrigation water management and incentivize farmers at large. An estimate of actual evapotranspiration derived from remote sensing techniques has the potential to improve irrigation water use efficiency (Eshete et al. 2020).

8.1.2. Nexus approach and optimization

Development of synergistic water use optimization plans based on climate, land use, agricultural water requirements and other ecological factors as well as economic benefit will support effective and efficient resource uses. That is of high importance in the face of changing climate. Multi-dimensional optimization approach proposed based on supply-demand approach to fight the supply and demand imbalances due to climate impact in China has brought better resilience in that region (Li et al. 2022). They found that synchronization and prioritization of the resources use (use efficiency, allocation equity, economic benefit, biological productivity, and environmental effects) and social, economic, ecological and environmental benefits has improved the water use balances. In this aspect, in the CRV sub-basins (Ketar, Meki, and Shalla), prioritizing of economically useful, environmentally feasible crops that withstand water shortage and fast growing varieties but highly edible as well as crops that gives high productivity per unit of water or per unit of land area used are important in improving the food security challenges in the region due to climate and excesive population growth.

Effective fertilizer application with irrigation water as an adaptation measure to climate change for maize production was also indicated for the CRV region. It offsets the severe impacts of yield loss in the area. In addition to that, positive effects of changing of planting date was observed for the maize crop production (Kassie et al. 2015).

Incorporating land use planning in a manner that its water allocations and use efficiencies will get improved, for instance, farm mechanization and land leveling to minimize water loses (Jat et al. 2015) is important. Water allocation planning based on wheather, soil and ecological charactersitics and social benefit priorities can also reduce unnecessary loss that may occur due to mis allocations (Li et al. 2022).

Cropping pattern alternatives that favors a better gain at a minimum total loss for water resource supply constraint that occurs in Pajero valley in the state of California were introduced with success stories (Garza-Díaz et al. 2019). Similarly, preparing alternative plans according to seasonal climate change scenarios for agricultural productions, land resource uses and water supply restriction plans that can mitigate the dual impacts of climate, and environmental changes while maximizing the benefits at lower total loses in production for the sub basins are thus necessary. Hence, the possible loss accomodation optimum plan should be further accessed, modelled and applied in the worst seasons. Obtaining a series of alternative allocation plans of agricultural water and land resource uses that response to dual change of environment both climate change and changes due to anthropologic interventions that give an in-sight into the system's comprehensiveness, equilibrium, and freedom to promote to the sustainable resource uses are important (Garza-Díaz et al. 2019). The plans need to be based on reliable data and studies carried out for the particular areas. This study aims to contribute to such a knowledge helping in the creation process of such adaptation plans for the CRVB irrigation development.

Comprehensive alternative water resource use planning that maximize the productivity of agricultural land and also that improves water loses and that sustains the sustainability of the environment are necessary. One of the best optimization options of agricultural water uses in the sub-basins is introduction of controlled irrigation that apply the water resources effeciently and that applies only the required amount of water at the proper time for effective use of the crops (Shao et al. 2015). Controlled irrigation also helps avoiding seepage and salinity problems via controlled irrigation water application to the required depth. Selecting fast growing and highly productive quality seeds together with controlled irrigation will help to save the resource for other economic and social uses. For instance, Kifle & Gebretsadikan, (2016) conducted an experiment on the controlled application of irrigation water for potato production in the water-scarce region of Tigrai in Ethiopia. They found positive effects of controlled irrigation water applications on potato production without losses for the deficit application of water with proper timing as means to curb water shortage due to climate changes (Kifle & Gebretsadikan 2016). In addition, selecting fast-growing, highly productive quality seeds will help to save the resource for other economic and social uses. Controlled irrigation is thus recommended as a mitigating strategy for water scarcity that would occur due to climate change and population growth in the sub-basins (Kifle & Gebretsadikan 2016).

For the CRVB, avoiding pollution of water sources and conserving the terminal lakes from pollution damage both from sedimentation and other environmental pollutions is important. Thus, controlling the water level of the lakes, avoiding the water quality degradations due to industrial and environmental wastes and improving the storage capacity in the sub-basins will favor better use of the resources during high periods in demand (Musie et al. 2020a; Worku et al. 2020).

Optimized nexus development and use plan for the use of water resources in the best priorities identified according to its economic and social benefits while safeguarding the environment sustainabily in hydroclimatic manner of each the sub-basin is cruicial (Li et al. 2022; Doelman et al. 2022). Therefore, the water-irrigation-land use and climate nexus synergies and tradeoff quantification of agricultural water requirement for a balanced resource use in multi model approach can help to properly use and balance the scarce resources (Doelman et al. 2022). Therefore, we would like to recommend the use of the water-agriculture-land use and climate nexus development and optimizations, and to enlarge it across the regions.

9. Conclusion and recommendations

This study investigated the impacts of climate and land use changes on the major components of the water balance in the central rift valley basin in Ethiopia from the temporal and the spatial points of view for the purpose of efficient irrigation water management. The evaluations are based on the magnitude of water yield, evapotranspiration and surface runoff components changed due to the changes in climate and land uses in relation to the base line data simulation outputs. Regional Climate Models (RCM) data in CORDEX - Africa (AFR- 44) were applied for the investigations. Data from the MIROC5-RCA4 ensemble driving climate models were downscaled, bias corrected and used for the analyses. The methodology followed an integrated modelling approaches with Arc-SWAT and Land Change Modeler (LCM) to assess for basin wide climate and land use change impacts and to search for optimum agricultural water management and adaptation strategies. For climate change, the study identified a general decrease in water yield and surface runoff and a seasonal increase in ET in the Ketar and Shalla sub-basins in both the near term (2031 - 2060) and long-term (2070 - 2099) periods when compared to the baseline periods (1984 - 2010). However, all the components projected show an increment in the Meki sub-basin for all the scenarios. The CRVB sub-basins were also found to be heterogeneous, and they showed variabilities in terms of their hydroclimatic reactions to the impacts of climate change. The level of the impacts of each of the representative concentration pathways (RCP2.6, RCP4.5 and RCP8.5) in each sub-basin were different. Though some similarities were found in the ways in which the pattern of the water balance component changes, however, the magnitudes of the impacts varied from sub-basin to sub-basin, between RCPs and between near term and long-term periods due to climate change. This indicates that each of the sub-basin has a unique water balance environment. The management interventions to the climate impacts should therefore be according to the sub-basins water balance sensitivities while respecting the whole hydrologically closed CRVB area water resources equilibrium.

Furthermore, water resources are influenced by different land uses, such as industrialization, urbanization, forestry, and agriculture. Understanding the conditions of the components of the water balance for the land use and land cover (LULC) changes is also an important factor for effective water management. In the finding, like climate change, changes in LULC mainly affect ET, surface runoff and water yield components of the water balance in the CRV sub-basins.

Increase in forest cover in the sub-basins resulted in runoff reduction and increase in evapotranspiration. Water yields were also affected by forest cover change and other land uses such as agriculture. Forest cover and its change was found to be the most decisive element affecting water balances followed by agricultural land use and range land changes. Thus, understanding the impacts of LULC changes on water resources can help engineers, planners, and managers to develop management and development strategies to reduce negative impacts of future LULC dynamics. It will also help the policy makers and government bodies to make better decisions on resource development and management.

Therefore, investigated land use and water resources management based on sub-basin specific interventions such as land use planning and management according to the impact mitigation strategies to improve the water yield and reduce unnecessary evapotranspiration loses in the Meki sub-basin is recommended. Likewise, afforestation and conservation in the Ketar will improve the water yield as the rate of evapotranspiration is comparatively low in this sub-basin. This can help to improve the water index of the region. In the Shalla sub-basin, high ET, low runoff but moderate water yield indicates the unique nature of the sub-basin, it means that lateral flow is higher. Therefore, groundwater recharge enhancement via integrated water and land use management, and selective plantation to reduce ET are very important.

The importance of integrated nexus synergies of crop water requirement (agronomic), soil moisture content (soil and water relationship) and evapotranspiration (climate impact quantification) determination as well as land use management are identified. Application of irrigation water use efficiency improvements with the help of remote sensors from satellite networks are recommended to easy the adaptation and mitigation strategies of irrigation development under severe climate and land use changes.

The integrated modelling approaches, the use of SWAT and LCM models, have proved to be a useful approach for analyzing and identifying the temporal and spatial conditions of the water balance at a basin scale in the faces of climate and land use changes for improving water use efficiency and management in irrigated farms.

The models are very good decision support tools for an informed decision-making process at local, sub-regional and regional levels. They also provide a basis for water management, soil and water conservation, irrigation technology selection, and for inter-basin water transfer controls, which are a coping mechanism against the impacts of climate and land use changes.

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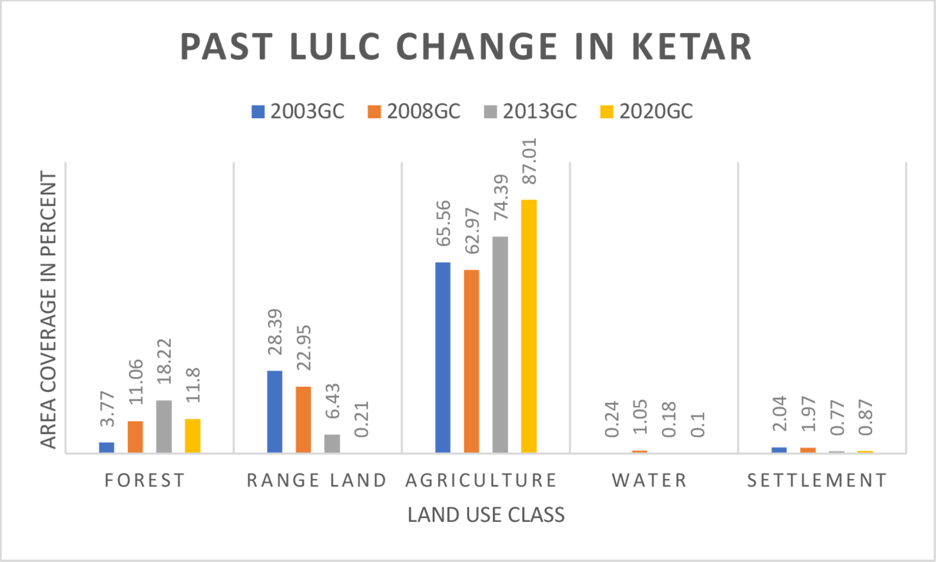
Appendices

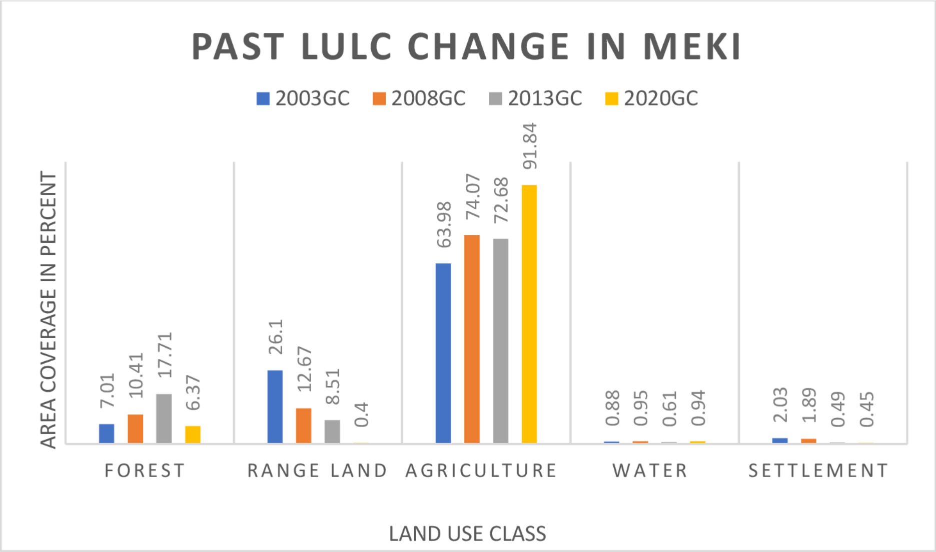
Appendix A. SWAT land use code and their description: Source: SWAT manual; ("SWAT" n.d.)

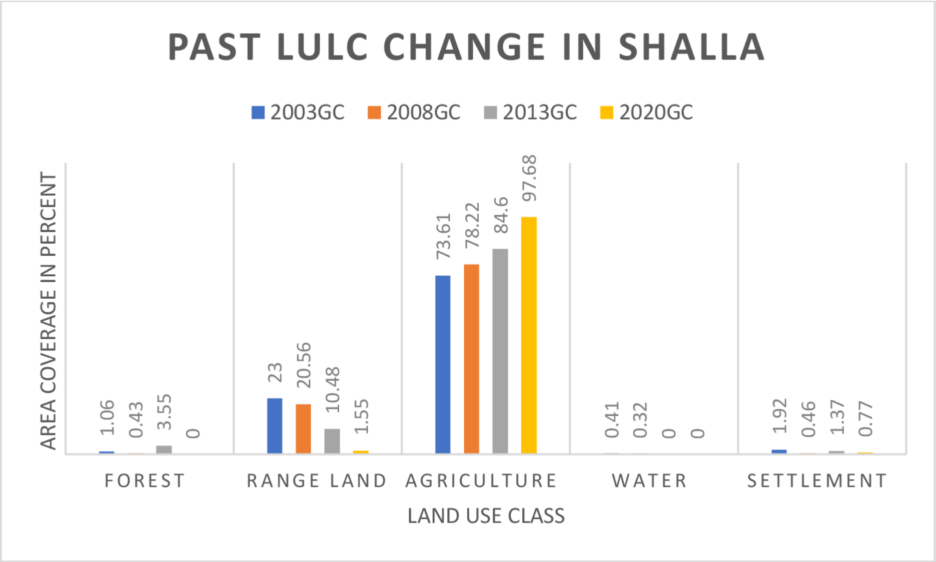
Object ID	LANDUSE	Land use describtions
1	AGRR	Cultivated Land; Rainfed; Cereal Land Cover System; lightly stocked
2	RNGB	Shrubland; Open (20-50 % woody cover)
3	RNGE	Grassland; lightly stocked
4	RNGE	Grassland; unstocked (woody plant)
5	AGRR	Cultivated Land; Rainfed; Cereal Land Cover System; moderately stocked
6	AGRR	Cultivated Land; Rainfed; Cereal Land Cover System; unstocked (woody pl)
7	RNGE	Grassland; moderately stocked
8	WATR	Wetland; Open water
9	RNGB	Shrubland; Dense (>50 % woody cover)
10	BARR	Bareland; Exposed sand / soill
11	BARR	Bareland; Exposed rock
12	RNGE	Woodland; Dense (>50 % tree cover)
13	FRSE	Forest; Montane coniferous; Open (20-50 % crown cover)
14	RNGE	Woodland; Open (20-50 % tree cover)
15	ORCD	Forest; Plantation forest; Open (20-50 % crown cover)
16	AGRL	Cultivated Land; Shifting cultivation; lightly stocked
17	AGRL	Cultivated Land; Shifting cultivation; moderately stocked
18	FRSE	Forest; Riparian; Open (20-50 % crown cover)
20	URMD	Urban
21	WETN	Wetland; Seasonal Swamp / Marsh
22	AGRC	Cultivated Land; Irrigated
23	FRST	Forest; Montane mixed; Open (20-50 % crown cover)
24	RNGB	Afro-alpine; Erica / Hypericum
25	RNGE	Afro-alpine; Grassland / Moorland
26	WETN	Wetland; Perennial Swamp / Marsh
27	FRSD	Forest; Montane broadleaf; Open (20-50 % crown cover)
28	FRSE	Forest; Bamboo; Highland Bamboo; Dense (50-80% crown cover)
29	FRSE	Forest; Riparian; Dense (50-80 % crown cover)
30	FRSE	Forest; Bamboo; Highland Bamboo; Open (20-50 % crown cover)
32	FRSE	Forest; Montane coniferous; Dense (50-80 % crown cover)
33	ORCD	Forest; Plantation forest; Closed (>80 % crown cover)
34	FRST	Forest; Montane mixed; Closed (>80 % crown cover)
35	FRSD	Forest; Montane broadleaf; Dense (50-80 % crown cover)
37	AGRR	Cultivated Land; Perennial crops; Enset/Root LC System; lightly stocked
38	FRSE	Forest; Lowland semi-evergreen; Closed (>80 % crown cover)
39	FRSE	Forest; Lowland semi-evergreen; Dense (50-80 % crown cover)
40	FRSE	Forest; Lowland semi-evergreen; Open (20-50 % crown cover)
42	FRSD	Forest; Montane broadleaf; Closed (>80 % crown cover)
43	FRST	Forest; Montane mixed; Dense (50-80 % crown cover)

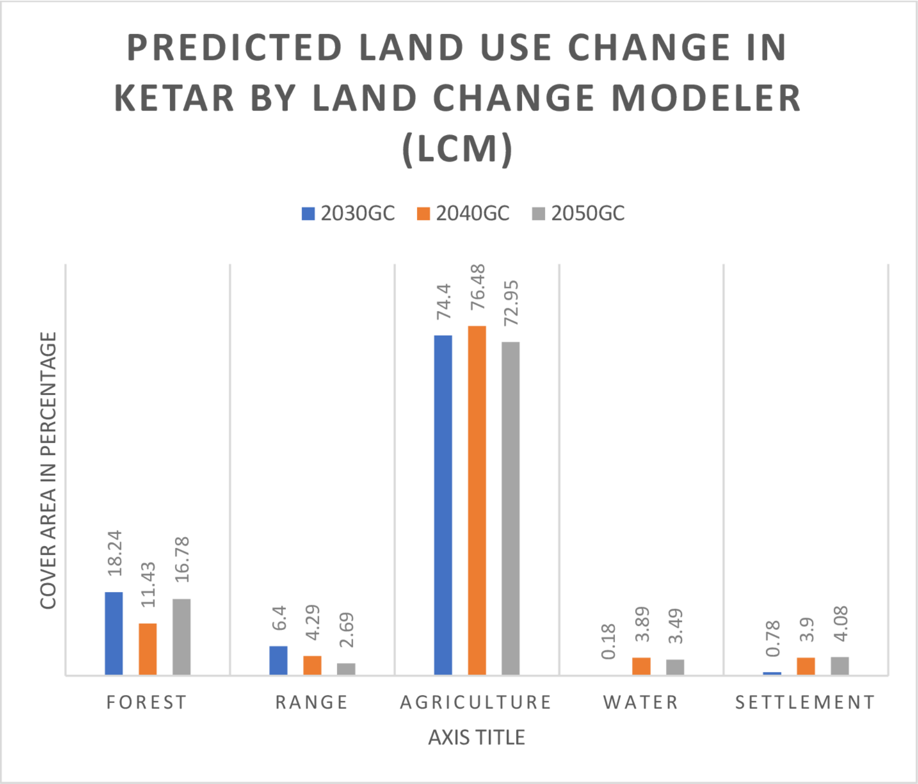
Appendix B. Past and predicted LULC cover area changes in percentage in the sub-basins

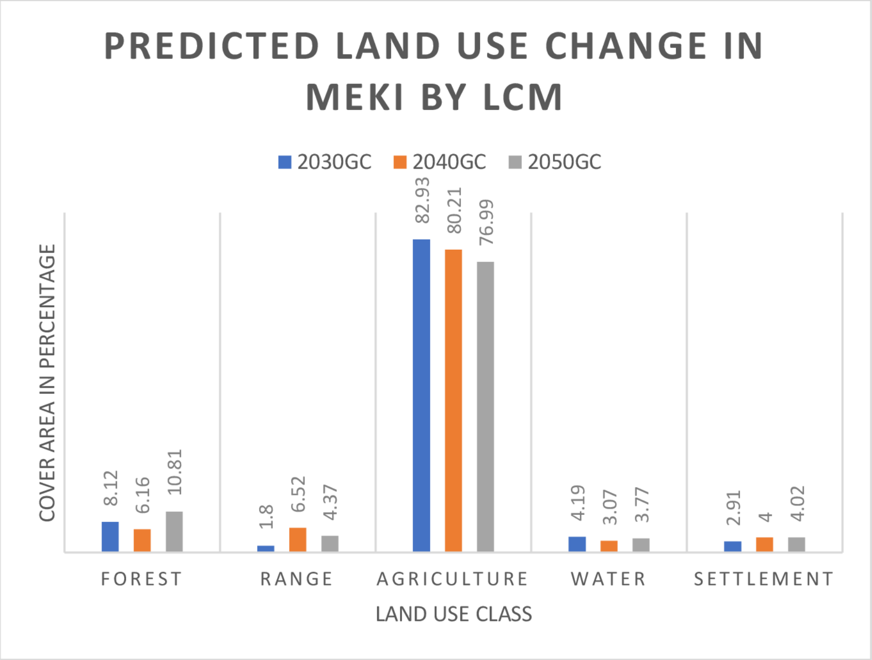


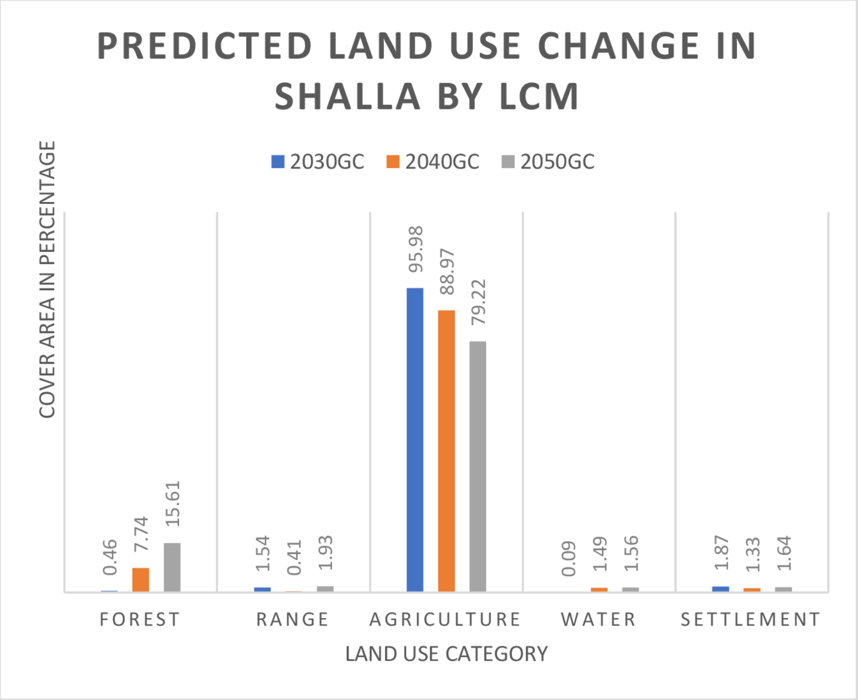
Note: GC *stands for Gregorian calendar*




PAST LULC CHANGE IN SHALLA
2003GC
2008GC
2013GC
2020GC
AREA COVERAGE IN PERCENT
1.06
0.43
3.55
0
23
20.56
10.48
1.55
73.61
78.22
84.6
97.68
0.41
0.32
0
0
1.92
0.46
1.37
0.77
FOREST
RANGE LAND
AGRICULTURE
WATER
SETTLEMENT
LAND USE CLASS


PREDICTED LAND USE CHANGE IN KETAR BY LAND CHANGE MODELER (LCM)
2030GC
2040GC
2050GC
COVER AREA IN PERCENTAGE
18.24
11.43
16.78
6.4
4.29
2.69
74.4
76.48
72.95
0.18
3.89
3.49
0.78
3.9
4.08
FOREST
RANGE
AGRICULTURE
WATER
SETTLEMENT
AXIS TITLE


PREDICTED LAND USE CHANGE IN MEKI BY LCM
2030GC
2040GC
2050GC
COVER AREA IN PERCENTAGE
8.12
6.16
10.81
1.8
6.52
4.37
82.93
80.21
76.99
4.19
3.07
3.77
2.91
4
4.02
FOREST
RANGE
AGRICULTURE
WATER
SETTLEMENT
LAND USE CLASS


PREDICTED LAND USE CHANGE IN SHALLA BY LCM
2030GC
2040GC
2050GC
COVER AREA IN PERCENTAGE
0.46
7.74
15.61
1.54
0.41
1.93
95.98
88.97
79.22
0.09
1.49
1.56
1.87
1.33
1.64
FOREST
RANGE
AGRICULTURE
WATER
SETTLEMENT
LAND USE CATEGORY

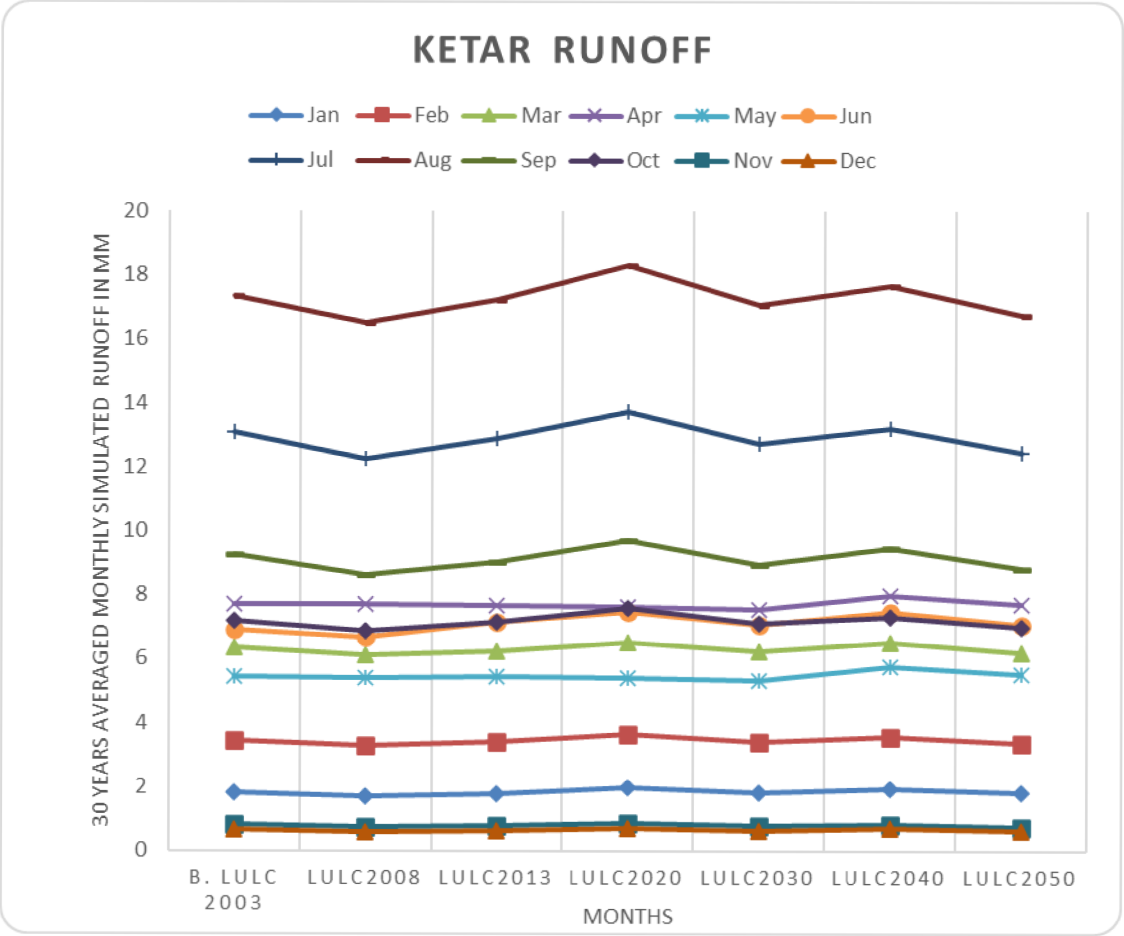
Appendix C. Locations of CORDEX grid points in the study areas.

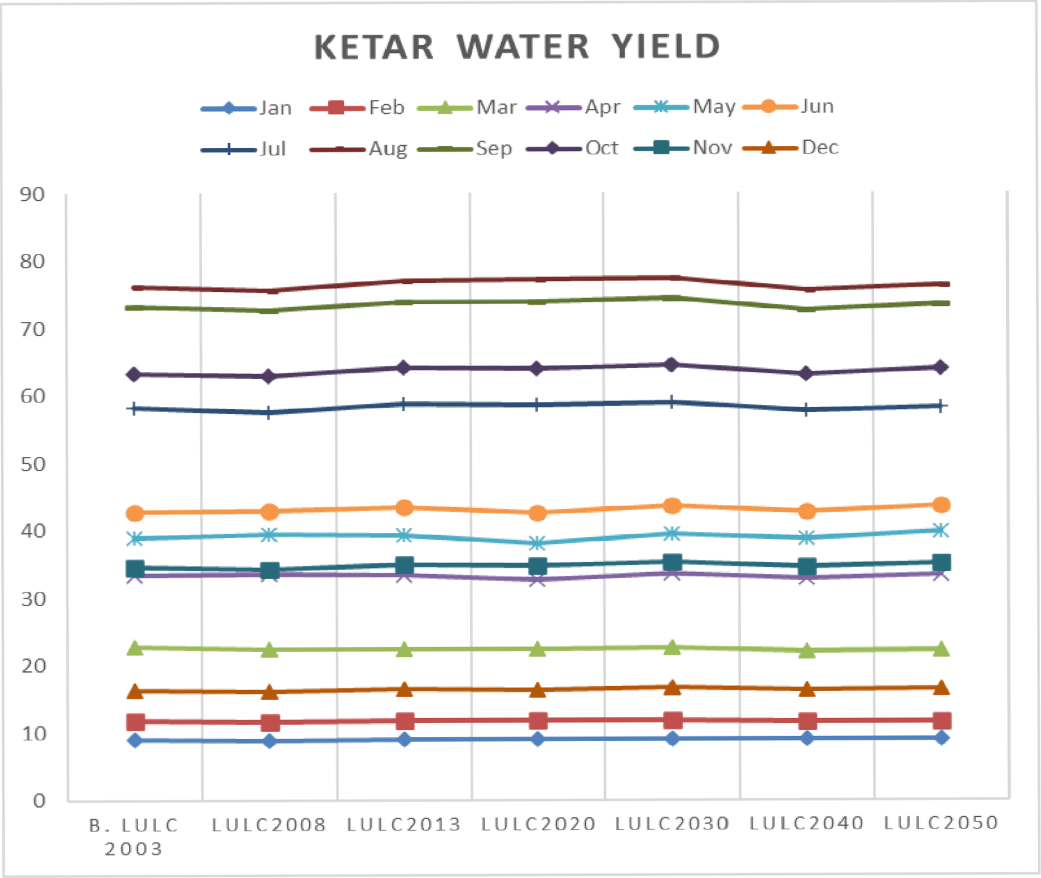
Station code	Station Name	Latitude (°)	Longitude (°)	Elevation (m asl)
1	CorS1	7.04	38.28	1864
2	CorS2	7.48	38.28	1988.5
3	CorS3	7.48	38.72	2093.38
4	CorS4	7.92	38.72	1986.89
5	CorS5	7.92	39.16	2281.24
6	CorS6	7.92	38.28	2131

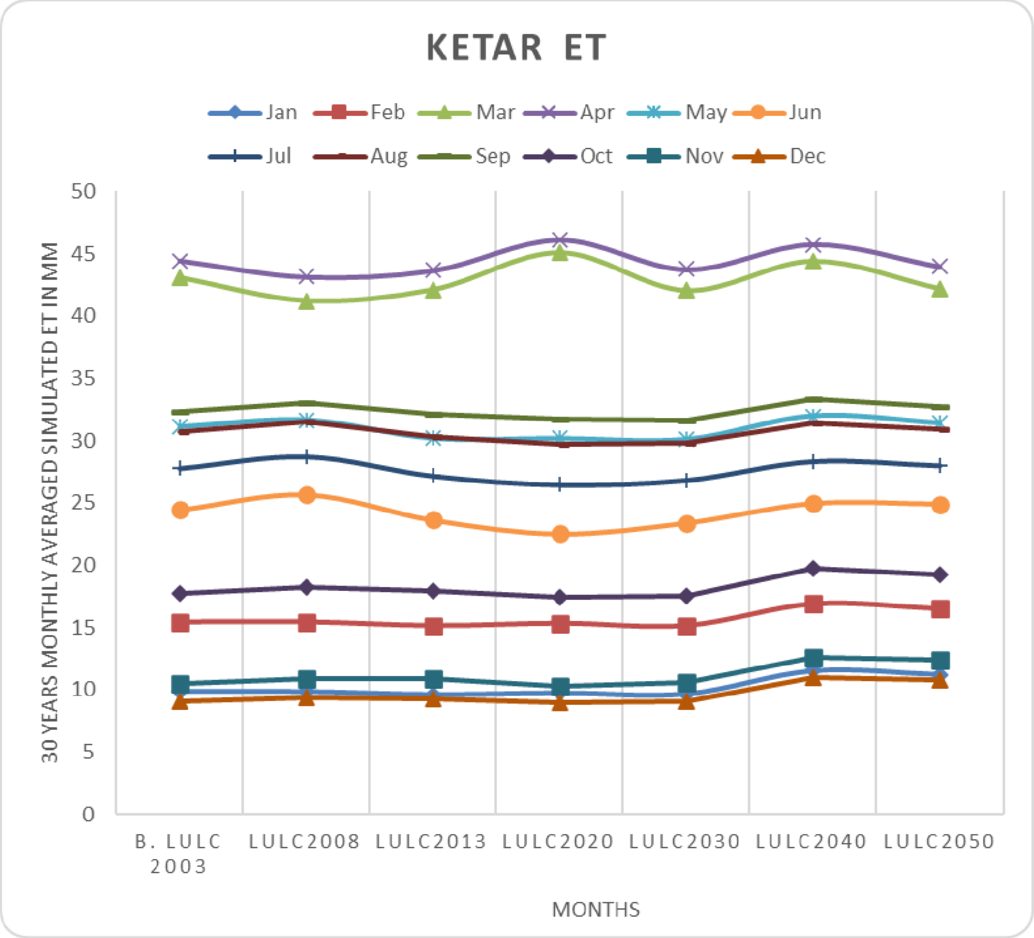
Appendix D. Climatic data input units.

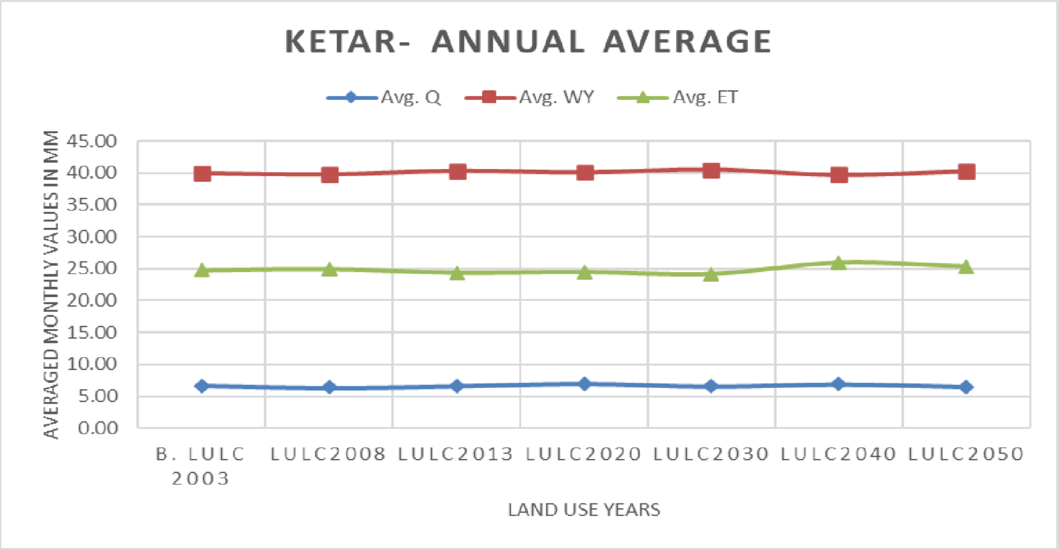
SN	Variable	Symbol	Unit
1	Precipitation rate	PREC	mm/day
2	Air temperature at 2m	TEMP	°C
3	Minimum air temperature at 2m	TMIN	°C
4	Maximum air Temperature at 2m	TMAX	°C
5	Relative Humidity	RHUM	%
6	Wind speed at 2m	WIND	m/s
7	Incoming surface solar radiation	SRAD	MJ/m^2 d

Appendix E. Monthly distributions and annual averages of components of the water balance in the Ketar sub-basin.

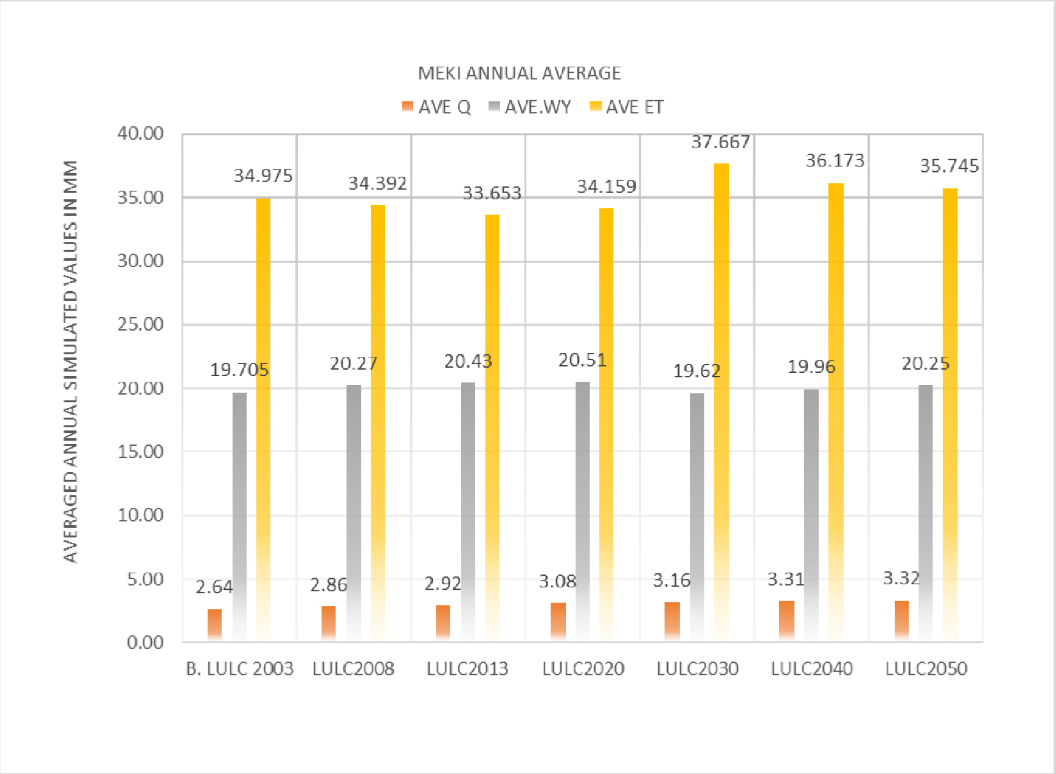



KETAR WATER YIELD
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
90
80
70
60
50
40
30
20
10
0
B. LULC 2003
LULC2008
LULC2013
LULC2020
LULC2030
LULC2040
LULC2050

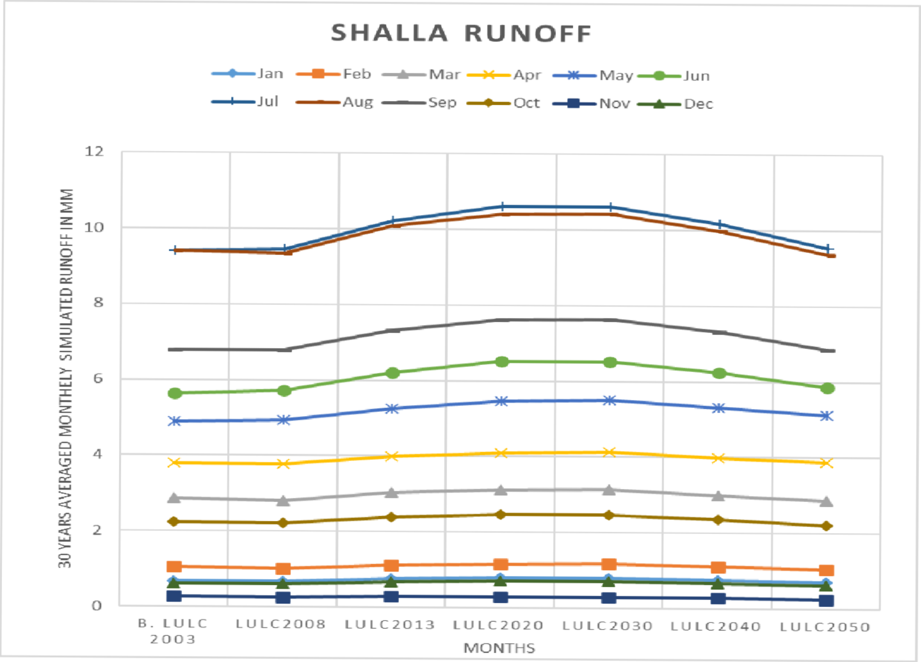

KETAR ET
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
30 YEARS MONTHLY AVERAGED SIMULATED ET IN MM
50
45
40
35
30
25
20
15
10
5
0
B. LULC 2003
LULC2008
LULC2013
LULC2020
LULC2030
LULC2040
LULC2050
MONTHS

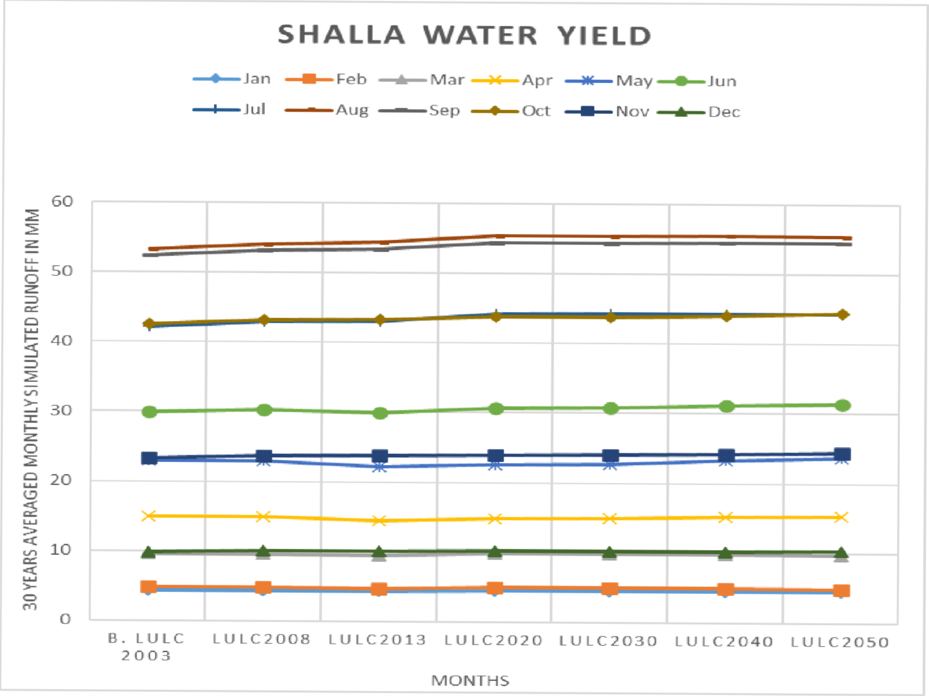

KETAR- ANNUAL AVERAGE
Avg. Q
Avg. WY
Avg. ET
AVERAGED MONTHLY VALUES IN MM
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
B. LULC 2003
LULC2008
LULC2013
LULC2020
LULC2030
LULC2040
LULC2050
LAND USE YEARS

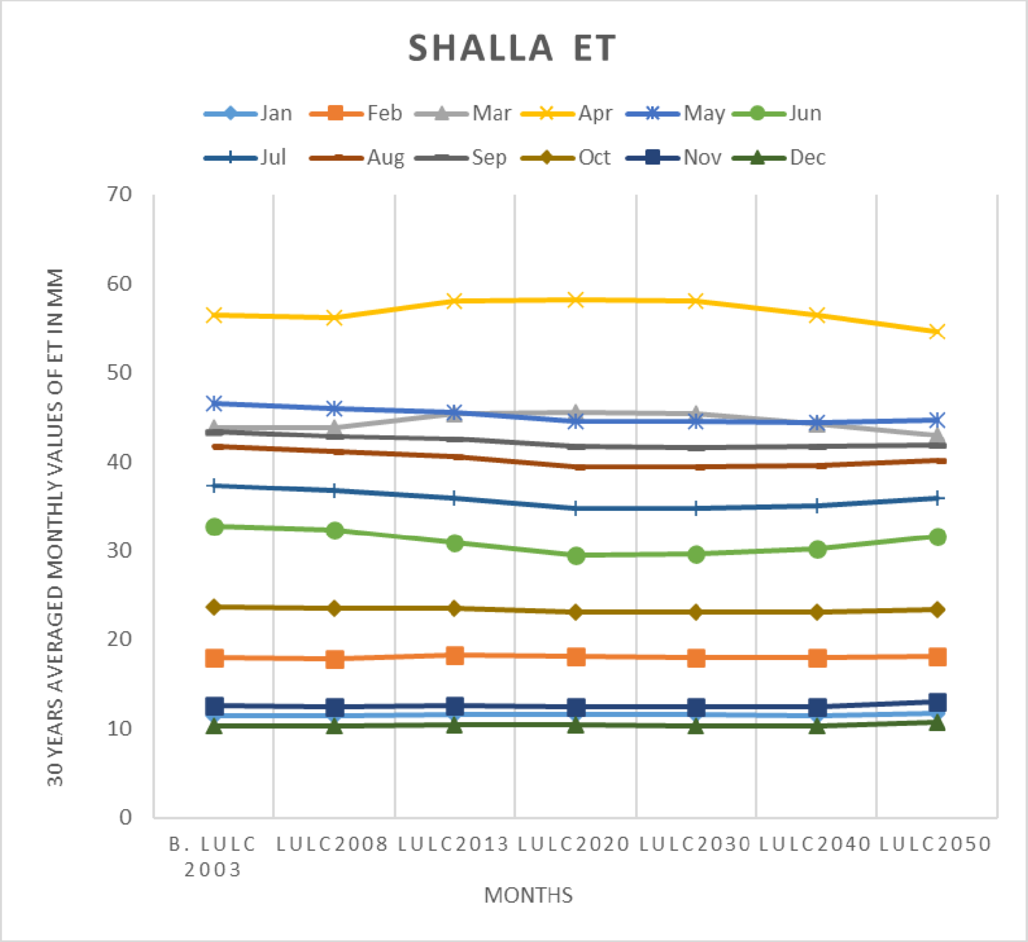
Appendix F. Meki sub-basin annual average distribution of the water balance components for each of the land use changes.



Appendix G. Shalla monthly distributions of the components of the water balance due to changes in land use.






SHALLA ET
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
30 YEARS AVERAGED MONTHLY VALUES OF ET IN MM
70
60
50
40
30
20
10
0
B. LULC 2003
LULC2008
LULC2013
LULC2020
LULC2030
LULC2040
LULC2050
MONTHS