Impacts of climate change on water and sediment flows in the Upper Tana Basin, Kenya

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Preface

The project “Water Infrastructure Solutions from Ecosystem Services Underpinning Climate Resilient Policies and Programmes” (WISE-UP to Climate) aims to demonstrate natural infrastructure as a “nature-based solution” for climate change adaptation and sustainable development in the Tana (Kenya) and Volta (Ghana-Burkina Faso) river basins. The Global Water Programme of the International Union for Conservation of Nature (IUCN) coordinates the global multidisciplinary partnership of WISE-UP that brings together various partners, including the International Water Management Institute (IWMI). The project is funded by the International Climate Initiative (IKI) of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB).

The work so far in the Upper Tana within the WISE-UP project showed that more in-depth understanding was needed on climate change impacts and land use management on water and sediment flows in the Tana basin. Therefore, the project started a collaboration with FutureWater, a research and consultancy organization with extensive local experience regarding these topics. This research was not originally envisaged under WISE-UP, but results from the first two year of project implementation have shown the importance of sedimentation within the Upper Tana basin and the downstream implications for hydropower production and water treatment.

The goal of this assignment is to evaluate the impacts of climate change on water resources and sediment in the Upper Tana. Also, an analysis was carried out to determine how climate change may affect an investment portfolio of sustainable water and land management activities in the Upper Tana. This final report summarizes the outcomes.

This study uses the hydrological model that was build for the Business Case study of the Nairobi Water Fund [Apse et al., 2015]. The authors would like to thank the staff of The Nature Conservancy and the Natural Capital Project that were involved in this study and the hydrological analysis, as well as the stakeholders of the Nairobi Water Fund that provided the necessary data to build the hydrological model.

Summary

Climate change will affect the water resources and ecosystem services in the Upper-Tana basin. Nowadays, this basin provides critical services (agriculture, water supply and hydropower) to society and sustains important biodiversity hotspots. An analysis was carried out of climate change impacts on water fluxes and sediment yields. The outcomes suggest that impacts on flows and sediment are high for some of the projections. Impacts on flows are generally negative: most of the projections show a decrease. For sediment load: some projections show an increase in loads while others a decrease.

The currently operational Upper-Tana Nairobi Water Fund is an important actor of change in the basin. The investment portfolio of the Business Case study of the Water Fund was analyzed in the context of climate change. The simulations with the investments and climate change confirm that investing in sustainable land management will still result in a considerable positive change for downstream services and users. For sediment loads, also under climate change, the investments show significant reductions – even slightly higher than under the current climate. For streamflow, affecting water availability downstream, the analysis shows that changes due to climate change are much larger than those caused by changes in land use management.

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Acronyms

ACCESS	African Collaborative Center for Earth System Sciences
BC3	Basque Centre for Climate Change
CM	Climate Model
CSIR	Council for Scientific and Industrial Research
BMUB	German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety
GWC	Green Water Credits
IKI	International Climate Initiative
IFAD	International Fund for Agricultural Development
ISRIC	International Soil Reference and Information Centre
IUCN	International Union for Conservation of Nature
IWMI	International Water Management Institute
JICA	Japan International Cooperation Agency
NCWSC	Nairobi City Water and Sewerage Company
ODI	Overseas Development Institute
RCP	Representative Concentration Pathway
RIOS	Resource Investment Optimization System
SRTM	Shuttle Radar Data Topography Mission
SWAT	Soil and Water Assessment Tool
SADC	Swiss Agency for Development and Cooperation
TARDA	Tana and Athi River Development Authority
TNC	The Nature Conservancy
WISE-UP	Water Infrastructure Solutions from Ecosystem Services Underpinning Climate Resilient Policies and Programmes
WRMA	Water Resources Management Authority

1 Introduction

1.1 Background

Water Infrastructure Solutions from Ecosystem Services Underpinning Climate Resilient Policies and Programmes (WISE-UP to Climate) is a project that aims to demonstrate natural infrastructure as a “nature-based solution” for climate change adaptation and sustainable development in the Tana (Kenya) and Volta (Ghana-Burkina Faso) river basins. The project is developing knowledge on how to use combinations of built water infrastructure (eg. Dams, levees, irrigation channels) together with natural infrastructure (eg. Wetlands, floodplains, watersheds) for poverty reduction, water-energy-food security, biodiversity conservation, and climate resilience. WISE-UP aims to demonstrate the advantages of combined built and natural infrastructure approaches using dialogue with decision-makers to agree acceptable trade-offs and linking ecosystem services more directly into water infrastructure development.

The Global Water Programme of the International Union for Conservation of Nature (IUCN) coordinates the global multidisciplinary partnership of WISE-UP that brings together the International Water Management Institute (IWMI), the Council for Scientific and Industrial Research in Ghana (CSIR), The African Collaborative Center for Earth System Sciences (ACCESS) - University of Nairobi, the International Water Management Institute (IWMI), the Overseas Development Institute (ODI), the University of Manchester, the Basque Centre for Climate Change (BC3), and IUCN. The project is funded by the International Climate Initiative (IKI) of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB).

WISE-UP is structured into a series of Work Packages and the work presented here falls under work package 2.1: quantification of water-related ecosystem services and climate change scenario modelling. The requirement for this work to be undertaken comes from technical discussions at the Partners Planning Meeting in October 2015 where it was highlighted that WISE-UP needs to better understand climate change impacts and land use management on water and sediment flows in the Tana basin. While this research was not originally envisaged under WISE-UP, subsequent results from the first two years of project implementation have shown the importance of sedimentation within the Upper Tana basin and the downstream implications for hydropower production and water treatment.

1.2 Previous work in the Upper Tana Basin

Over the last decades several researchers have studied the link between climate, water balance, erosion and sediments in the Upper Tana basin. The most relevant studies are selected and briefly summarized below.

1983: Sedimentation in the Tana basin reservoirs - [*Woolridge*, 1983]
The scale of the reservoir sedimentation problem in the Tana basin was first illustrated by Wooldridge [1983] who used hydrographic survey data to estimate a sediment inflow of 357 m3/ km2/year to the Kamburu reservoir on the Tana River. This represents a loss in storage volume of 17 million m3 (12%) in 18 years.

1992 – 1998: Study on the National Water Master Plan - [JICA, 1992]

The Study on the National Water Master Plan of 1992, published by the Japan International Cooperation Agency [*JICA*, 1992] gives a complete overview of water-related issues in Kenya, including the Upper Tana. In 1998 the "The Aftercare Study on the National Water Master Plan in the Republic of Kenya" was carried out, also by JICA. Relevant data on flows and sediment loads can be found in the accompanying Data Books.

1996: Multi-scale estimates of erosion and sediment yields - [Brown et al., 1996]

This study attempted to locate the major sources of sediment yield and measure erosion processes in the rainy season. They assessed sediment yield during the first years of operation of the Masinga dam to be between 0.6 and 0.9 million tons/year. They provide an overview of other studies in which sediment yield was assessed using various methods and for different time periods. Overall the estimates range between 0.3 and 7.5 million tons/year for the Upper Tana. Archer [1996] also studied the sources of sediments in the Upper Tana area and estimated specific sediment yield rates of about around 50 tons/km2 in the upper tea-cultivated zones, but much higher values in the lower areas up to around 2500 tons/km^2.

2006 – 2014: Green Water Credits - [Kauffman et al., 2014]

Green Water Credits (GWC) is a mechanism for payments to land users in return for specified soil and water management activities that determine the supply of fresh water at source and reduction of soil erosion from rainfed fields. Green Water Credits in Kenya started in 2006 and was coordinated by the International Soil Reference and Information Centre (ISRIC) and supported by the International Fund for Agricultural Development (IFAD) and the Swiss Agency for Development and Cooperation (SDC). Several studies were carried out [*Hunink et al.*, 2012] and the project was close to implementation in 2012 [*Kauffman et al.*, 2014]. Outcomes of the project were crucial in starting-up the Nairobi Water Fund studies led by The Nature Conservancy.

2009: Scoping assessment Climate Change and Hydropower - [*Droogers*, 2009]

FutureWater carried out a case study for an approach to analyze climate change impacts on hydropower production [*Droogers*, 2009]. A pessimistic and optimistic climate change projection scenario were analyzed, using first-order estimates of flows and reservoir sedimentation. The analysis showed that the impact of climate change without any adaptation strategies ranges from a positive US$ 2 million to a cost of US$ 66 million for the hydropower, irrigation and drinking water sector. Several adaptation strategies (demand-side and supply-side) were also explored.

2012-2013: Physiographic Survey on reservoir sedimentation - [Hunink et al., 2013]

A Physiographical Survey In The Upper Tana Catchment [*Hunink et al.,* 2013] was undertaken to assess the soil erosion and sediment loads in Upper Tana Catchment areas and estimate the impact of sediment deposition on the reservoir capacities of the principal dams. A physiographical baseline was established through an intensive monitoring campaign of flow and sediment loads throughout the basin, bathymetric surveys of the reservoirs and soil erosion modeling to assess the current situation. This study provides crucial data and outcomes on soil and erosion monitoring and modeling, sedimentation of the key reservoirs (6.7 Mton/year for Masinga, 0.9 Mton/year for Kamburu reservoir) and the current state and improvements of the monitoring networks.

2014 – current: Upper Tana-Nairobi Water Fund – A Business Case [Apse et al., 2015]

After a pre-feasibility study in 2013, a full Business Case study was carried out by FutureWater, the Natural Capital Project and The Nature Conservancy on the potential for the Upper Tana-Nairobi Water Fund, from a biophysical [*Hunink and Droogers*, 2015] and economic point of view. The study showed that there is clear business case for investing in upstream improved watershed management to reduce erosion, improve water quality and increase water availability, thus benefiting downstream services which are principally urban water supply and hydropower [*Vogl et al.*, 2016]. Climate change impacts were not taken into account in the study.

2015: Economics of Ecosystem Services of the Tana River Basin - [van Beukering and de Moel, 2015]
This study provides an assessment of the economic value of the positive and negative externalities of different water-flows regimes, both upstream and downstream in the Tana River basin. It gathers baseline information on the state of ecosystems, hydrological status and stakeholders, in order to increase the awareness of the significance of ecosystem services among policymakers. Also, it highlights different components that require more study, as for example the reduced sediment transport in the middle Tana due to sediment trapping in the upstream dams, and understanding climate change impacts.

2015: Baseline review and ecosystem services assessment of the Tana River Basin, Kenya - [Baker et al., 2015]
This study was carried out within the WISE-UP project and presents a basin-scale summary of natural resources within the Tana River Basin and illustrates an overview of how people living within the basin rely on a wide variety of ecosystem services. In addition, the paper puts forth a first approximation of the key role natural infrastructure plays in supporting efforts to ensure water-energy-food security in the Tana River Basin.

1.3 Current developments

Several projects are taking place in the Upper Tana related to water resources management and agriculture. The principal actor is currently the Nairobi Water Fund which focuses on improving watershed conditions locally, to reduce erosion and sedimentation into streams and to improve agricultural practices at the scale of individual farms and stream reaches. Funds are raised by The Nature Conservancy and local NGOs from both public and private sources.

The water fund is moving forward with the USD 1M per year investment plan with a fundraising goal of USD 10M. The initial 2-year investment plan (approved July 2016) is fully funded, and the fund is targeting regional “hotspots” of activity based on the results of the Business Case study [*Vogl et al.*, 2016], mainly in the Thika/Chania watershed, a sub-basin of the Upper Tana. Currently, a major strategy of the Nairobi Water Fund has been to engage farmers with capacity-building and technical assistance, expecting that once benefits are realized, farmers will have direct economic incentives to continue the practices on their own without relying on direct payments.

The water fund assumes that a combination of constraints related to capital, risk tolerance, ability to cope with extreme weather events, and lack of information contribute to current lack of adoption, and that these constraints can be overcome by farmer extension efforts and assistance with inputs and materials, while requiring farmers show good faith effort via their own in-kind contributions of labor and land. Ongoing monitoring of project uptake and participation, as well as socio-economic and hydrologic monitoring has been implemented to allow for ongoing hypothesis testing and course correction.

The Nairobi Water Fund has a public-private Steering Committee, which is an independent and transparent governance mechanism for managing the Water Fund. In this Steering Committee are among others members of the Nairobi City Water and Sewerage Company, KenGen, TARDA

(Tana and Athi River Development Authority) and Water Resources Management Authority (WRMA).

The “Upper Tana Natural Resources Management Project” is another project of relevance from which different activities have been funded related to water and sediments. The project started in 2012 and will end in 2020 and is funded by the Government of Kenya, International Fund for Agricultural Development (IFAD), Spanish Trust Fund and the Local community. The project has two development objectives namely (i) increased sustainable food production and incomes for poor rural households living in the project area; and (ii) sustainable management of natural resources for provision of environmental services.

1.4 Objectives

The objective of this study was to evaluate the impacts of climate change on water resources, erosion and sediment fluxes in the Upper Tana basin (i.e. upstream of the Masinga Reservoir). The analyses provided insight into how climate change can influence the biophysical effectiveness of different land management options in the Upper Tana, focusing on flows and sediments that influence downstream services, mainly hydropower.

The hydrological model that was developed for the Nairobi Water Fund Business Case study was used and the simulations carried out for the Thika/Chania watershed. Outcomes on sediment yield were then upscaled to the Upper Tana using previous assessments. Climate change scenarios were used that are selected in the WISE-UP project. The land management activity portfolio of the business case study was used to evaluate the impact of climate change on these investments.

2 Methods

2.1 Approach

To assess climate change impacts on the hydrology of the Upper Tana basin, this study made use of the modelling tool and model inputs that were prepared for the Business Case study for the Upper Tana-Nairobi Water Fund [*Vogl et al.*, 2016]. The model was forced with several climate change projections, and simulation outputs of the water and sediment flows were analysed.

The approach followed for the business case study integrated a prioritization model to allocate the type and location of conservation investments in the different sub-basins, subject to budget constraints and stakeholder concerns (Resource Investment Optimization System – RIOS). These portfolios were then evaluated using the Soil and Water Assessment Tool (SWAT; Arnold et al., 1998) to simulate spatially explicit changes in water yield and suspended sediment at different levels of investment. The analysis focused on the benefits that would arise over a 30-year time horizon from a USD 10M investment in these sub-watersheds disbursed over a period of 10 years.

The SWAT model for the Water Fund study was built, calibrated and validated for a baseline period of the years 2000 to 2012. For more details on the model inputs, calibration and validation and setup of the SWAT model, please refer to [*Hunink and Droogers*, 2015; *Vogl et al.*, 2016].

For the Nairobi Water Fund, three priority watersheds were selected (Figure 1). From these three, for the current study the Thika/Chania watershed was selected because of its critical contribution to Nairobi's water supply (90%). The SWAT model for this watershed has an area of 836 km2 with in total 189 sub-basins, and 2124 calculation units (so-called Hydrological Response Units) with an average size of 0.4 km2/unit.

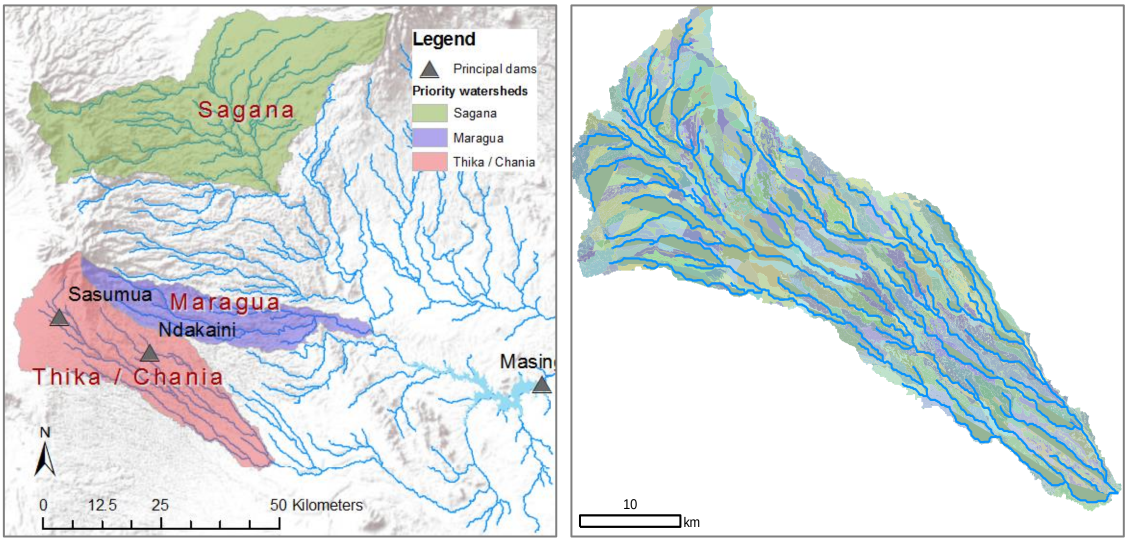

Figure 1 Left: the 3 priority watersheds used in the Nairobi Water Fund business case study. Right: the Thika/Chania watershed with polygons representing the calculation units of the model

To understand the impact of climate change, in the current study, a total of 6 scenarios were analysed that were provided by the WISE-UP project. These climate projections were used to force the calibrated SWAT model, assuming the same land-use and cropping patterns as in the current situation. These 6 scenarios were analysed for 3 future periods (see more details hereafter). The delta change method was applied to adjust the model with the climate model projection forcings, using monthly delta change factors [e.g. *Andersson et al.*, 2006].

2.2 Data

An overview of the datasets that were used for the SWAT model are provided in the Business Case study of the Nairobi Water Fund [*Apse et al.*, 2015] and are summarized in Table 1.

Table 1 Overview of datasets that were used for the SWAT model

Dataset	Detail, resolution, scale	Source
Digital Elevation Model	90 meter resolution	Shuttle Radar Data Topography Mission (NASA)
SOTER-UT	Scale 1:250 000	ISRIC-WISE
TNC-Africover	15 meter resolution	TNC
Meteorological data	Daily 2000-2012	WRMA, Physiographic Survey (2011) data
Streamflow	Daily 2000-2012 of several stations within watersheds	WRMA
Turbidity	Ngethu intake	NCWSC
Sediment loads	Point data of 2010	WRMA, NCWSC, Phyisiographic Survey (2011)
Bathymetric survey	Of 2010, reservoirs Masinga, Sasumua, Thika	Phyisiographic Survey (2011)

Digital elevation data were obtained from the Shuttle Radar Data Topography Mission (SRTM) of the NASA’s Space Shuttle Endeavour flight on 11-22 February 2000. The dataset was resampled to the same resolution as the land use map (15m).

The most detailed and complete dataset on soils including soil property estimates for the Upper Tana was prepared within the Green Water Credits project [*Batjes*, 2010]. The data set was derived from the 1:250 000 scale Soil and Terrain Database for the Upper Tana (SOTER_UT, ver. 1.0) and the ISRIC-WISE soil profile database, using standardized taxonomy-based pedotransfer procedures.

For the Nairobi Water Fund study, a detailed update of the Africover land use maps was made, using satellite imagery, detailed maps from stakeholders and ground truth points. The final pixel resolution of these maps is 15 m. These high resolution maps were used as input for the SWAT model.

WRMA provided data on the meteorological stations in the watersheds, that were complemented with data from the 2011 Physiographic Survey and with data from NCWSC of the stations they manage.

Streamflow data were obtained from WRMA for 11 stations, of which 5 were found to be reasonably complete and sufficiently reliable for model calibration. Also data on Masinga inflow were used for validation.

Sediment turbidity data were obtained from NCWSC for the Ngethu intake. In addition, long-term sediment loads were available based on the bathymetric survey carried out in 2010 of the Masinga dam and the NCWSC dams.

2.3 Reservoir sediment budget

The simulation outputs for the Thika/Chania catchment were upscaled to the Upper Tana basin (upstream of Masinga). The main reference source for this upscaling was the bathymetric survey carried out in 2011 [*Hunink and Droogers*, 2011]. These measurements were performed under favorable conditions with Masinga near to full supply level during the survey. Based on the bathymetric survey and after considering trapping efficiency of the reservoir, and sediment consolidation, a sediment budget was derived (see Figure 2) for the reservoirs Masinga and Kamburu. These indicated that the Masinga reservoir has lost around 10% of its capacity since 1981, and the Kamburu reservoir (a much smaller reservoir) around 15% since 1983. For the upstream NCWSC reservoirs (Nadakaini and Sasumua) no significant sedimentation was found due to scouring and their relatively low trap efficiency.

The mentioned study estimated a mean annual sediment inflow of 8.0 Mtons/year and a sedimentation rate of 6.7 Mton/year. For the upscaling to the Upper Tana basin, this was assumed to be a representative value under current conditions. It has to be noted that this may be a conservative estimate: the rates estimated based on the bathymetric survey were based on a timespan that includes years in which the watershed was likely in relatively better condition with lower erosion rates. It is likely that there has been a certain increasing trend in degradation over time during this period, which would mean that the 8.0 Mtons/year is an underestimate. But as no data are available on land degradation over this period, this was not considered in this study and the value was assumed to be representative for current conditions.

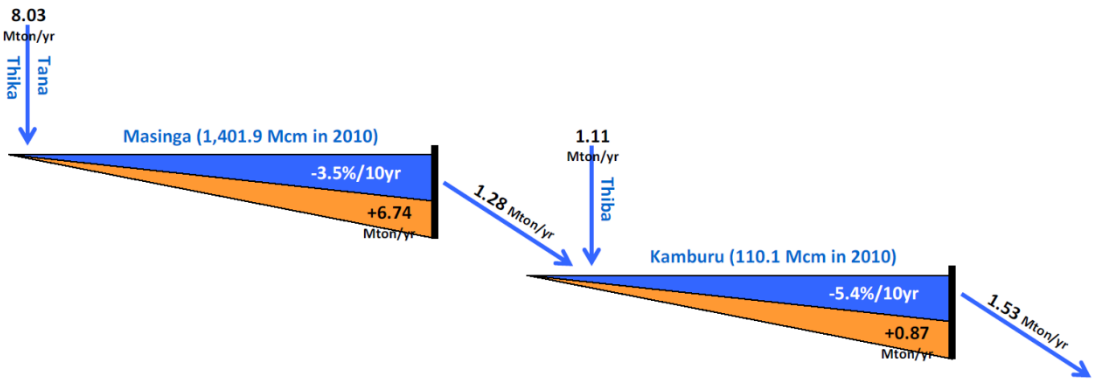

Figure 2 Sediment budget for the Masinga and the Kamburu reservoir [*Z&A*, 2011]

The ratio between the mean long-term sediment yield from the Thika/Chania catchment and the total sediment inflow into the Masing reservoir was used to estimate the reservoir sediment budget under different future scenarios. Additional details of the upscaling methods are provided in Section 3.4.

2.4 Climate projections

To analyze the impact of climate change on sediments and streamflow in the Thika/Chania watershed, the existing SWAT model was forced with modified forcings for precipitation and temperature from different climate change scenarios. Outputs of three different climate models were selected for this study, as listed in Table 2. Results of these models were derived for two different Representative Concentration Pathways (RCPs): 4.5 and 8.5.

Table 2 Climate scenarios under consideration in this study.

SCENARIO ID	CLIMATE MODEL	INSTITUTE	RCP
CM1	CAnESM2	CCCMa	4.5
CM2	CAnESM2	CCCMa	8.5
CM3	EC-Earth	ICHEC	4.5
CM4	EC-Earth	ICHEC	8.5
CM5	CNRM-CM5	CNRM/CERFACS	4.5
CM6	CNRM-CM5	CNRM/CERFACS	8.5

The climate projections were analyzed for three future periods:

1. Near future: 2030s (2026-2045)
2. Long-term future: 2050s (2046-2065)
3. Far horizon: 2080s (2076-2095)

Figure 3 gives an overview of the annual average temperature that was obtained for the Thika/Chania watershed for each of the climate projections. Figure 4 shows the same but for annual precipitation values. The boxes of the boxplots show the interannual variability within the period. These values are based on averaged climate model outputs for each of the model grid points within the watershed.

Climate model outputs were available from 2006 onwards. Generally, a period length of 20 years is considered a minimum to identify climatic trends. A period shorter than 20 years is not considered representative enough and could give too much weight to certain low or high extremes that fall within the period. The “2010s”, using climate model outputs between the years 2006 and 2025 was considered as the period representing current conditions. Part of this period lies in the future and is outside of the baseline period of the SWAT model (2000 – 2012). Thus, the changes compared to the baseline may suffer a slight underestimation due to this minor mismatch. For this study this was however considered acceptable and in any case, the results presented can be considered to be conservative.

For the future periods, also time spans of 20 years were used. Other modeling efforts in the WISE-UP project use periods of 30 years (so for example for the Near Future, 2020-2049, instead of 2026-2045 as used here). It was verified that this difference has a minor impact on the study outcomes (<3% difference in precipitation and temperature forcings).

Figure 3 shows that mean annual temperature will increase considerably, for all climate scenarios. Particularly a large increase is predicted for the 2080s period for the RCP 8.5 scenarios. Interannual variability remains more or less constant or increases.

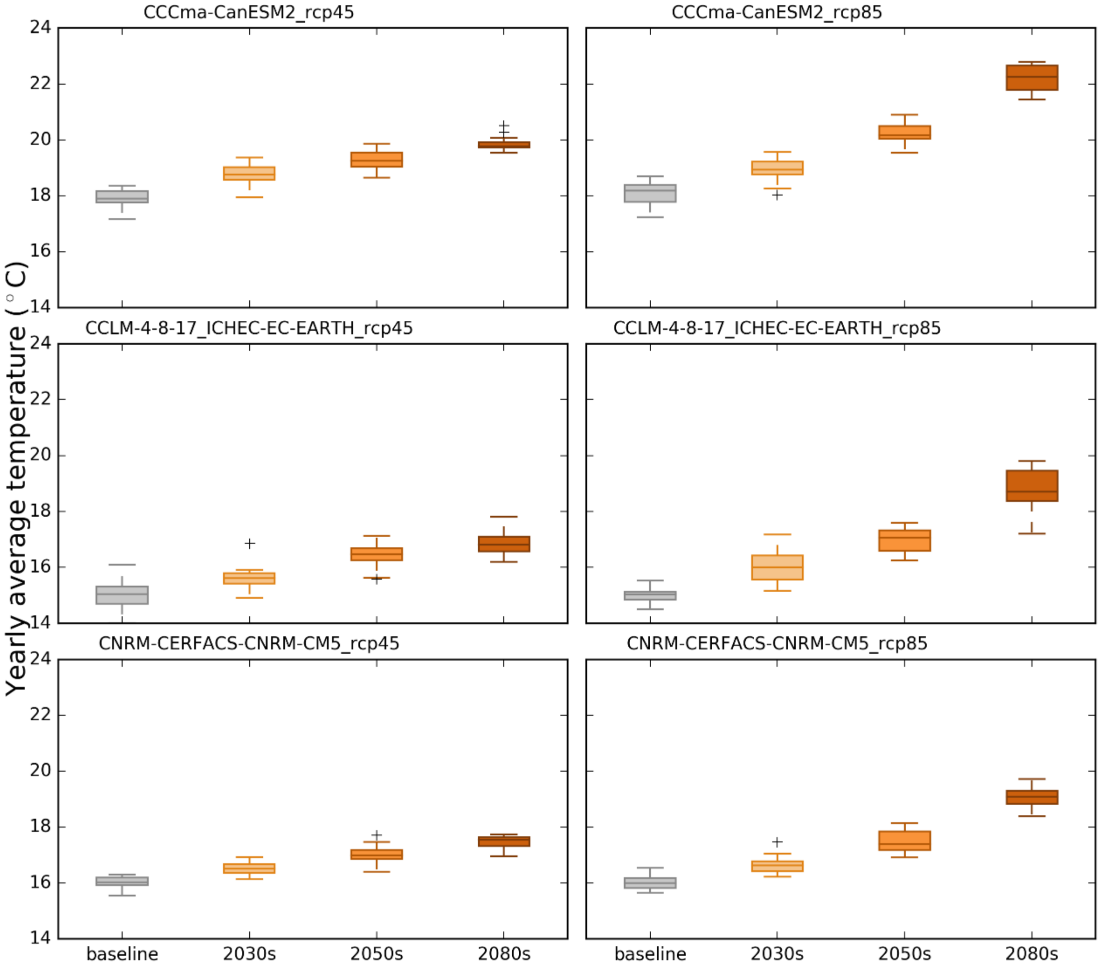

Figure 3 Boxplots of annual average air temperature for each period, according to the selected climate scenarios

The annual precipitation predicted by the six climate scenarios (Figure 4) does not show a clear trend (mean annual values shown afterwards in Table 3 however provide some more guidance). A gradual rise is observed for CM5, whereas CM2 and CM3 projections are characterized by a gradually decreasing yearly rainfall amount. The range in annual values is relatively large in most scenarios, in particular for CM3 and CM4.

Another observation from Figure 4 is that the annual values for the 2006-2025 period differ substantially. Especially for CM1 and CM2 they are relatively high, compared to the other models and to the values actually observed in the basin. For this reason, commonly bias correction is carried out, to make sure that the baseline of the climate model predictions actually agree with the observations in the area of interest.

A common way to avoid the need for bias correction, is by using the relative changes of the climate model predictions, instead of the actual predicted values. This has been implemented for this study. The relative changes seen in the climate model predictions have been applied to the observations that were used as input into the hydrological model. This approach is sometimes also referred to as the “delta change” approach and is very common for this type of assessments [*Diaz-Nieto and Wilby*, 2005; *Immerzeel et al.*, 2008]. There are other more advanced techniques, like quantile mapping, that consider predicted changes in the rainfall intensity distribution, but this was beyond the scope of this study.

The delta change approach is generally applied using monthly means of the variables of interest (precipitation and temperature in this case). Mean monthly values are calculated for

a) The 2006-2025 climate model predictions
b) The climate model predictions of the future periods.

Then the relative difference between (a) and (b) is applied to the baseline observations to make future projections. The baseline observations are the same for all climate projections, as these consist of the model inputs into the original SWAT model from [*Hunink and Droogers*, 2015]. For precipitation, the relative change is used, while for the temperature the absolute difference in ºC is used.

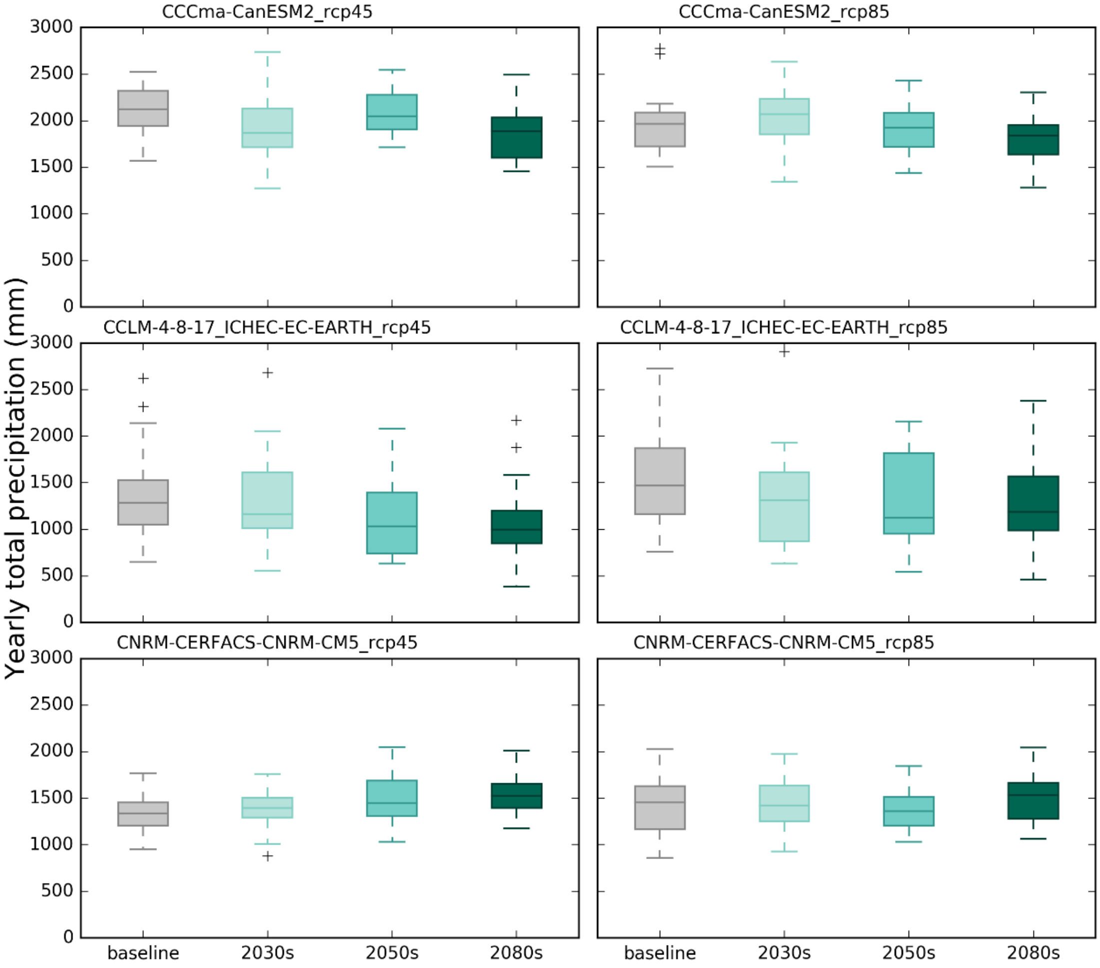

Figure 4 Boxplots of annual precipitation for each period, according to the selected climate scenarios

Figure 5 shows the changes in average monthly temperature for each future period and climate projection, calculated with respect to the baseline period (2006-2025). The changes are expressed in absolute values (ºC change). All scenarios predict increases of mean monthly temperature for all months of the year. RCP 8.5 scenarios predict a gradual increase in temperature up to a difference of 2 to 4 °C, depending on scenario and month, while this rise is significantly smaller in the RCP 4.5 scenarios.

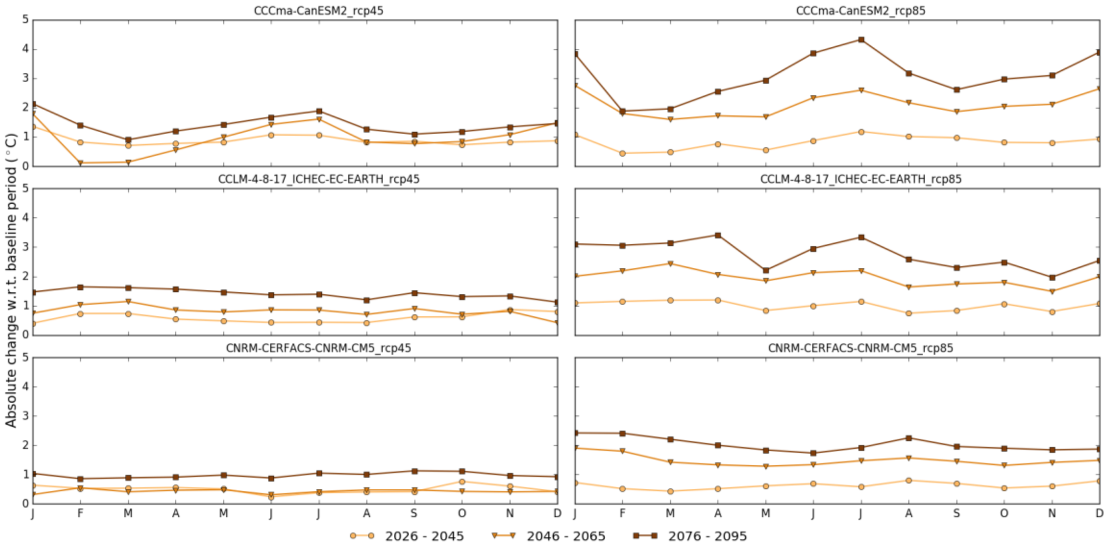

Figure 5 Projected changes in average monthly air temperature for each climate scenario and each period.

Figure 6 shows the relative changes for monthly precipitation. The values shown are factors, e.g. 0.5 meaning that precipitation in that month is predicted to increase by half. As can be seen, there is no overall trend in the projections: some climate models predict generally an increase in most months, others a decrease in precipitation. Overall the trend is slightly more negative (more hereafter).

For CM2, quite extreme values for precipitation increase have been found in the projections for January and February (factors between 2-3). Also for the first period in CM6 high values have been found but less extreme than for CM2. Especially the increases as seen in CM2 seem too high and may be due to local errors in the climate model parameterization. In consultation with the WISE-UP project team it was decided to leave CM2 out of the analysis.

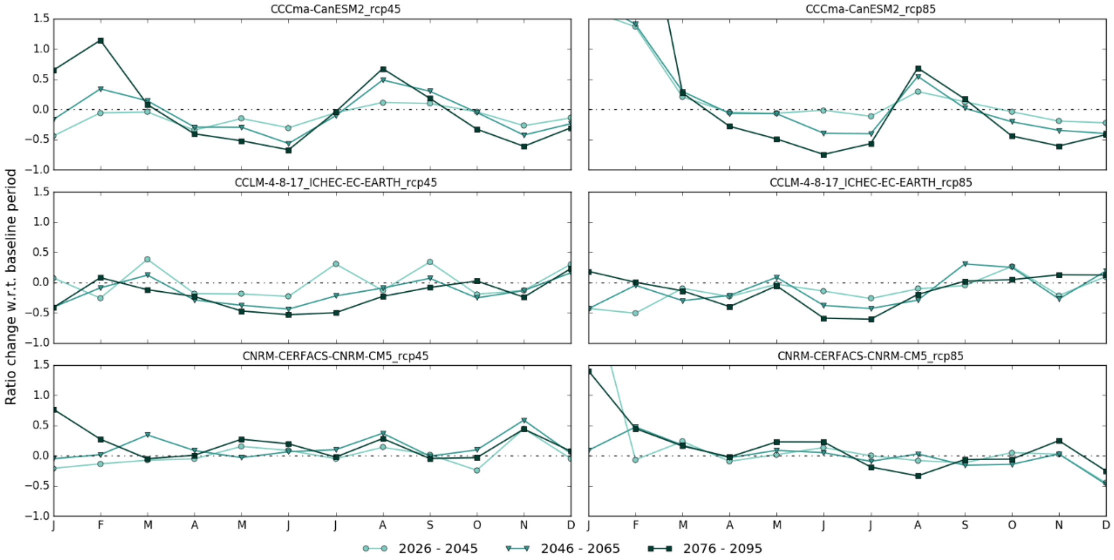

Figure 6 Projected changes in average monthly precipitation for each climate scenario and each period. The zero line (dashed) corresponds with the 2006-2025 predicted monthly precipitation according to the respective climate model.

Figure 7 shows how the relative changes affect absolute mean monthly precipitation values, and compares the projected precipitation to the SWAT model baseline (2000-2012). For the two wet seasons: CM1, CM2, CM3 and CM4 predict lower rainfall compared to the current climate. CM5 and CM6 show an increase in precipitation for the wet seasons. For the two dry seasons no clear signal can be extracted, although overall the trend is slightly more negative than positive.

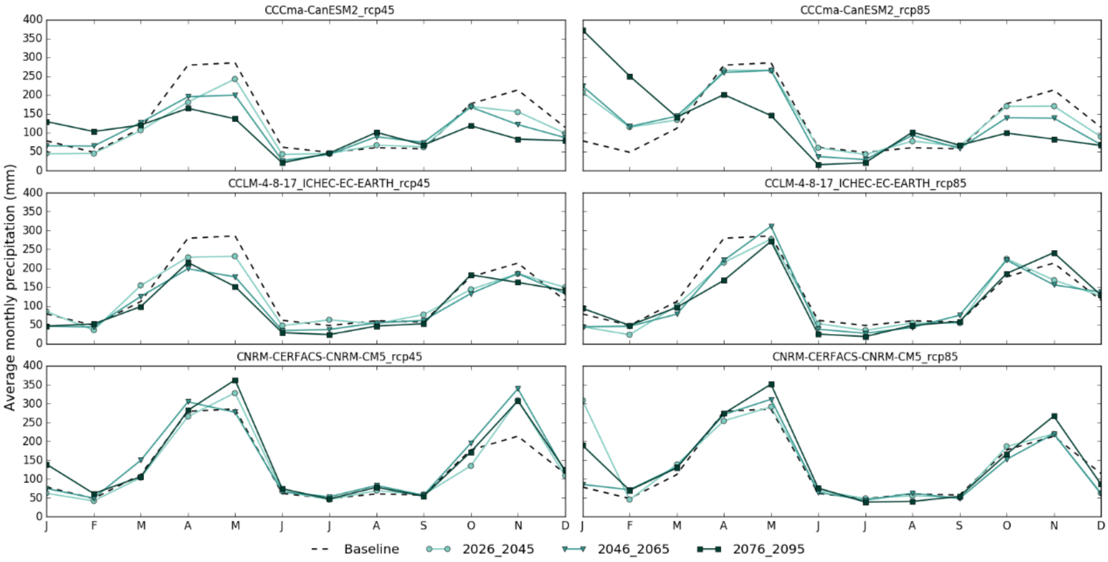

Figure 7 Projected average monthly precipitation for each climate scenario and each period, including baseline conditions for the Thika/Chania watershed. Note that the "Baseline" is equal for all scenarios, as it represents the 2000-2012 SWAT inputs.

For annual precipitation values, Table 3 shows the mean values for all periods and climate projections. The arrow shows whether the prediction is higher or lower than current (1537 mm). As was also seen in Figure 4, some climate projections predict an increase in precipitation in the future, others a decrease.

Table 3 Mean annual rainfall (mm) in three future periods, for different climate scenarios, as used in the SWAT model. Arrows indicate whether deviations from the current annual average (1537 mm) are positive or negative

Scenario	2026-2045	2046-2065	2076-2095
CM1	↓1262	↓1264	↓1172
CM2	↑1663	↑1575	↑1566
CM3	↓1454	↓1231	↓1202
CM4	↓1378	↓1399	↓1384
CM5	↑1596	↑1768	↑1809
CM6	↑1732	↓1524	↑1743

The hydrological model SWAT for the Thika/Chania watershed was run with these climate projections for rainfall and temperature. The total number of model runs were:

- 3 future periods and 6 climate projections = 18
- A "Business As Usual" (no activities of the Water Fund) and Investment scenario = 2
- In total 18 x 2 = 36 simulations (excluding the already existing simulations of the baseline)

As mentioned before, the CM2 results are not shown in the result section and were not included in the analysis as the rainfall predictions were considered too inconsistent with the rest of the projections.

3 Results

3.1 Climate change impacts on streamflow

Changes in precipitation and temperature will affect the water balance of the Upper Tana basin and thus the water provision to downstream water users. The principal outgoing fluxes of the basin water balance are actual evapotranspiration (ET) and the streamflow leaving the basin.

Table 4 gives an overview of average annual ET in the basin under different future scenarios based on the SWAT simulations. These simulated ET values represent the water that the vegetation can extract from the soil for transpiration and soil evaporation, and thus depend on both changes in temperature (increased potential evapotranspiration) as well as changes in precipitation.

For the current conditions, the mean ET for the Thika/Chania watershed is 716 mm. As can be observed, for some of the climate scenarios a decrease in annual ET is predicted. For other simulations, rainfall and temperature values lead to an increase in the soil water available for ET. The full range of values stretches from a minimum of 640 mm up to a maximum of 758. Averaging the 5 projections, the predicted decrease is -2% for the first two periods, and -3% for the last period.

Table 4 Annual actual evapotranspiration (mm) as computed by SWAT, for each future period and climate scenario, and relative changes compared to current

SCENARIO	2026-2045		2046-2065		2076-2095	
CM1	665	-7%	679	-5%	661	-8%
CM3	714	0%	660	-8%	640	-11%
CM4	673	-6%	675	-6%	673	-6%
CM5	718	0%	755	5%	755	5%
CM6	744	4%	728	2%	757	6%

Monthly average streamflow at the basin outlet, as computed by SWAT, is depicted in Figure 8. Looking at the main wet period from March until May, all climate scenarios agree reasonably for the 2026-2045 period, with values not differing much from the baseline (except for CM1). However, the range of predicted streamflow values in this season increases further into the future. The dry period from June to October is not predicted to undergo significant changes. Streamflows from October to February are rather uncertain, given the large range of different results dependent on the climate projection used.

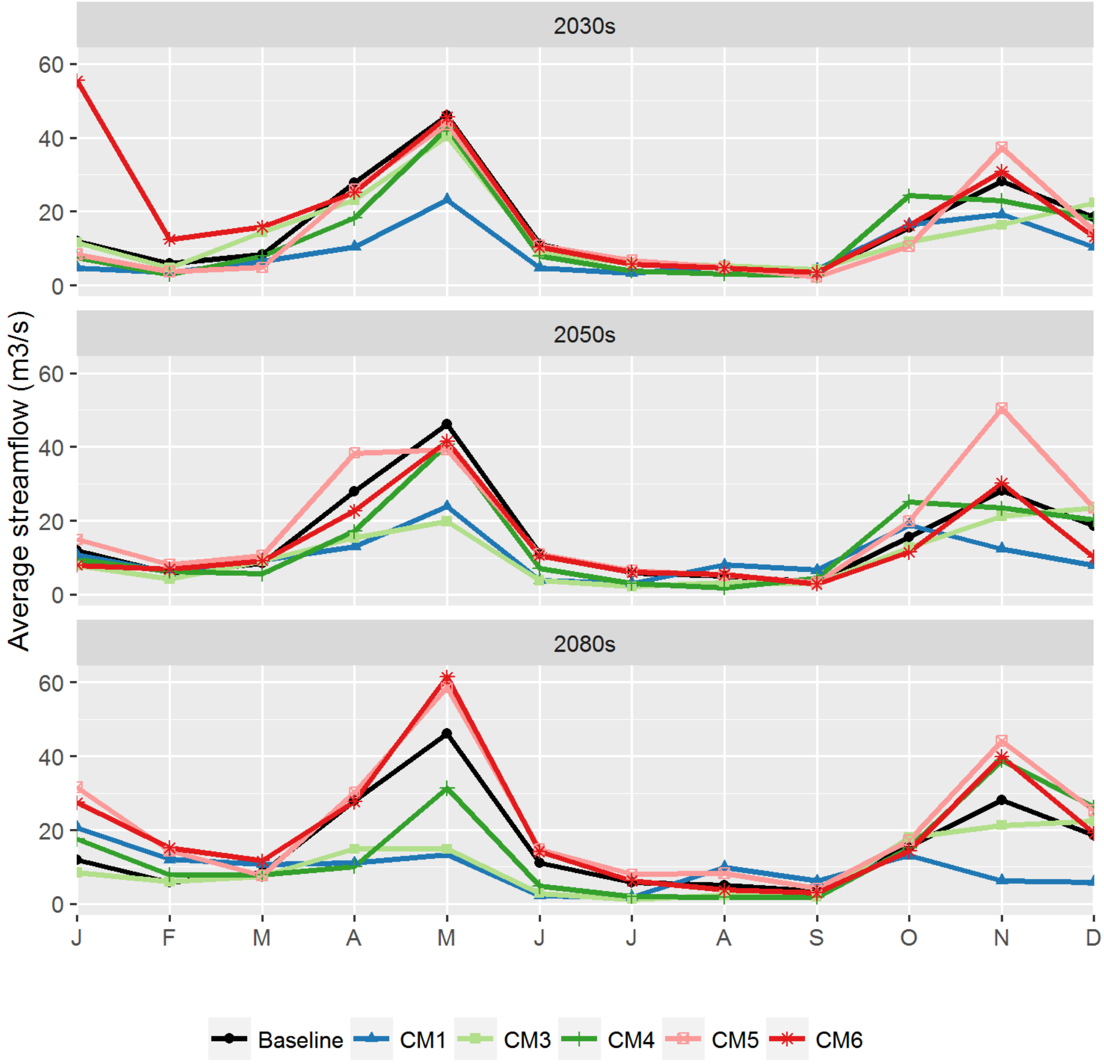

Figure 8 Monthly streamflow patterns at the basin outlet, for different periods and climate projections, for the business-as-usual scenario

As is clear from Figure 8, but also from Table 5, the projections deviate considerably. CM1 predicts a decrease of 40% in flows, while for example CM6 predicts an increase of 30%, in the first period (2030s). Taking the mean of the projections in this study (see last column of Table 5), we see a slight decrease of about 9% in the first period, and 5% in the last period (2080s).

Table 5 Mean flows (m3/s) for different projections and periods

Period	Current	CM1	CM3	CM4	CM5	CM6	Mean all proj.
Current	15.7						15.7
2030s		9.3	14.1	13.5	14.5	19.9	14.3
2050s		10.3	10.5	13.7	19.2	13.8	13.5
2080s		9.4	10.2	13.8	22.0	20.3	15.1

The flow duration curve based on SWAT results is presented in Figure 9 (based on monthly values). On the low-flow end of the curve, there are two categories of scenarios that can be distinguished. CM1, CM3 and CM4 predict a shift of the curve to the left, with flows of +/- 1 m^3/s being equaled during 92% of the time, rather than 98% under baseline conditions. CM5 and CM6 do not predict any substantial changes on this side of the curve. For the remaining part of the curve, the impact of climate change is less pronounced, with often three climate scenarios on either side of the baseline curve.

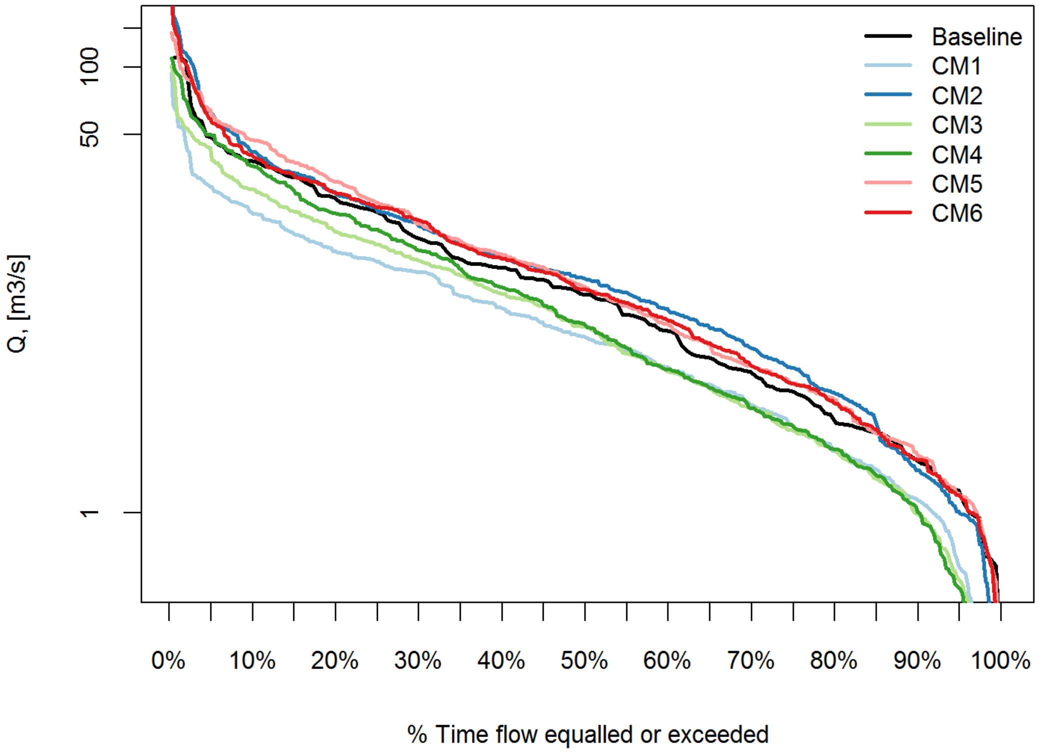

Figure 9 Monthly flow duration curve at basin outlet, under different climate change scenarios

The SWAT model enables the impacts at the different points of interest in the watershed to be assessed. Figure 10 shows for 3 points in the watershed the mean annual flow (boxes showing interannual variability), for the different periods and projections. The 3 points of interest selected are:

- Thika reservoir,
- Chania river before the inlet from Thika,
- The outlet of the Thika/Chania watershed

The orange box shows the variability during the baseline period.

For the 2030s and 2050s, the CM6 projection (RCP 8.5) shows an increase in streamflow, with increasing interannual variability. The other 4 projections show generally a decrease in flows, and mostly a decrease in interannual variability. For the last period, CM5 (RCP 4.5) also predicts increases in flows.

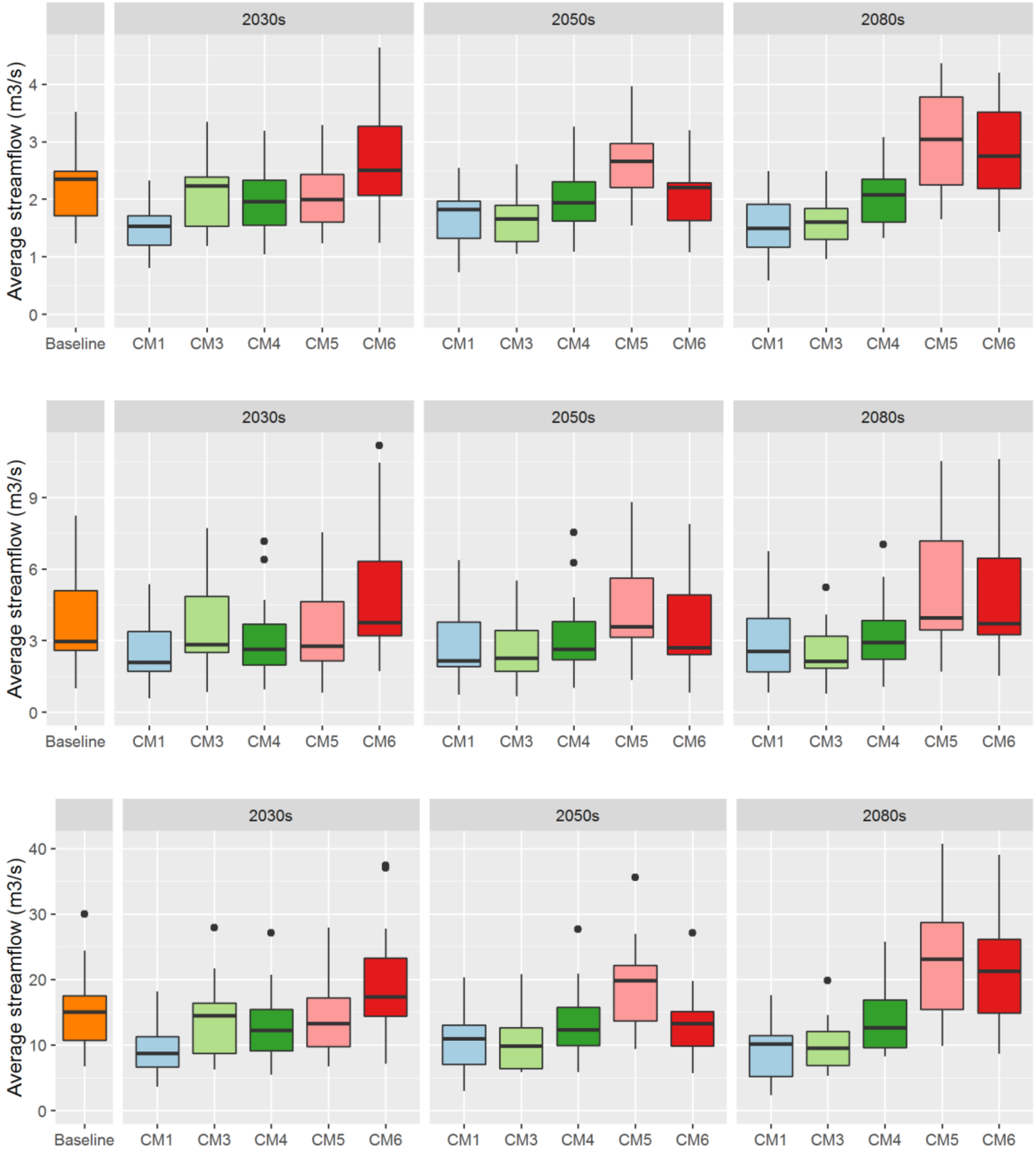

Figure 10 Boxplots of average annual streamflow at Thika Reservoir (upper), Chania (middle) and basin outlet (bottom), for different periods and climate change scenarios. The dots are values outside of the interquartile range.

3.2 Climate change impacts on erosion rates and sediment load

Monthly sediment concentrations at Mwagu intake under each of the future scenarios are shown in Figure 11, with respect to the baseline run. Similar as with the streamflow results, it is difficult to observe a clear trend. Most scenarios predict a decrease in sediment concentration during the March – May rainy season, due to lower flows and thus lower sediment transport capacity of the stream. For other parts of the year (especially January – March in 2076-2095) an increase in sediment concentration is predicted.

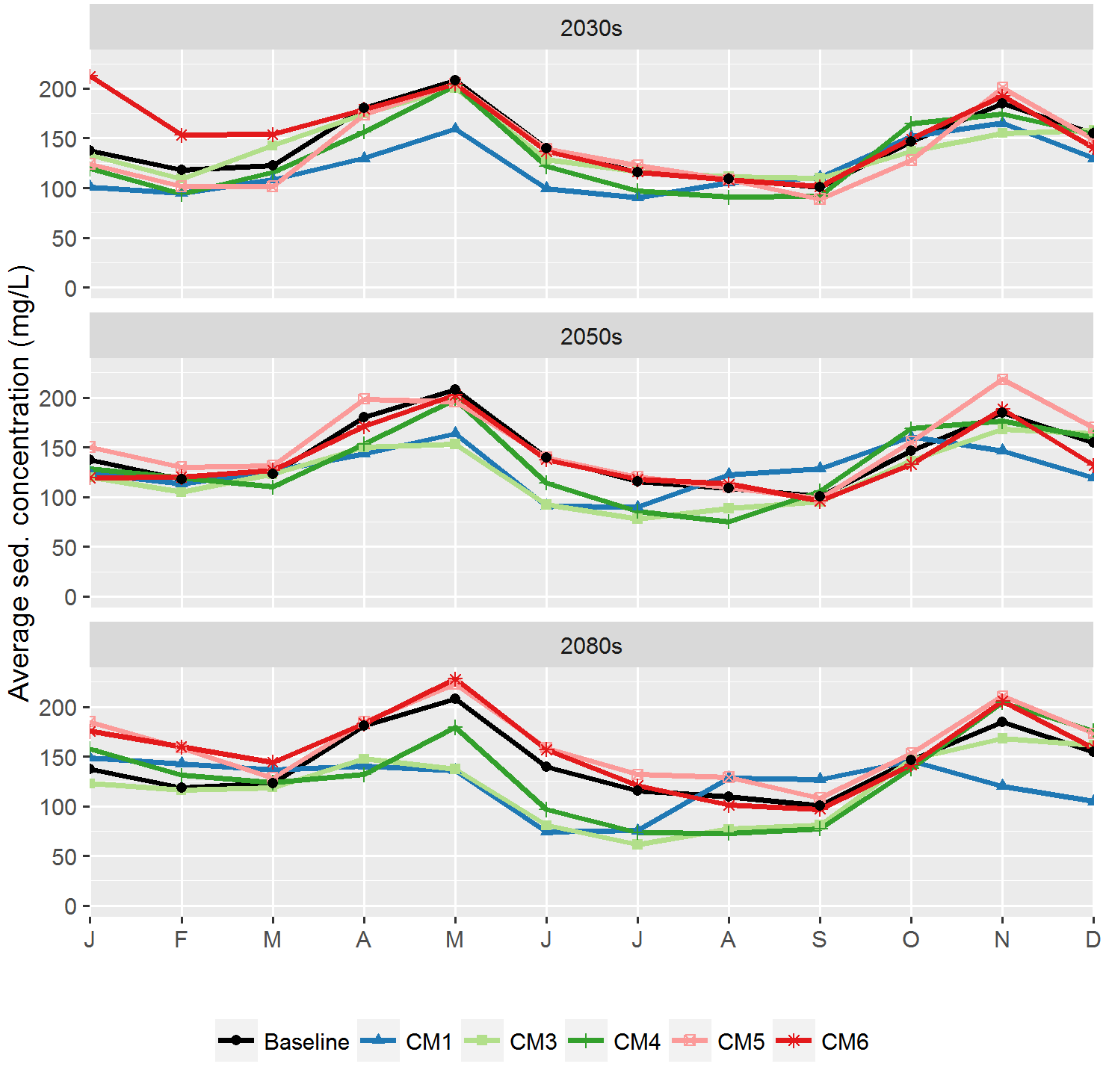

Figure 11 Monthly patterns of sediment concentration at Mwagu intake under baseline conditions and different climate change scenarios

Table 6 shows the mean annual sediment yield predicted by the different projections for the 3 future periods, compared to current (first column). As can be seen, CM1 and CM3 (both RCP 4.5) show considerable reductions in sediment yield (related to decrease in precipitation in this projection), to about half of current conditions. CM5 and CM6 show the largest increase, of up to more than 50% in the first period. Overall, the mean of all the projections show a slight decrease in sediment load (last column). It has to be noted that the approach assumes that the rainfall intensity distribution in the future climate is the same as in the current climate. For certain areas, climate models predict changes in the rainfall intensity distribution (e.g. lower precipitation amounts, but more intense) that can be relevant to erosion processes, but this was not studied here.

Table 6 Mean annual sediment yield (Mton/yr) leaving the Thika/Chania watershed, for different projections and periods

Period	Baseline	CM1	CM3	CM4	CM5	CM6	All proj.
Current	1.9						1.9
2030s		1.0	1.5	1.5	2.3	3.0	1.9
2050s		1.0	0.9	1.6	2.7	1.9	1.6
2080s		0.9	0.9	1.5	3.1	2.8	1.8

Annual sediment load is highly variable in the Thika/Chania catchment. Figure 12 shows boxplots based on annual sediment loads for the entire watershed, and for the different projections and periods. The interannual variability is predicted to increase considerably under several of the projections. The mean annual changes of sediment loads are greater than with flows (Figure 10) due to the highly non-linear behavior of erosion and sediments. Also here it can be observed that several projections predict a decrease in sediment loads. This is mainly related to a decrease in flows in these projections, which reduces sediment transport capacity especially during the rainy season.

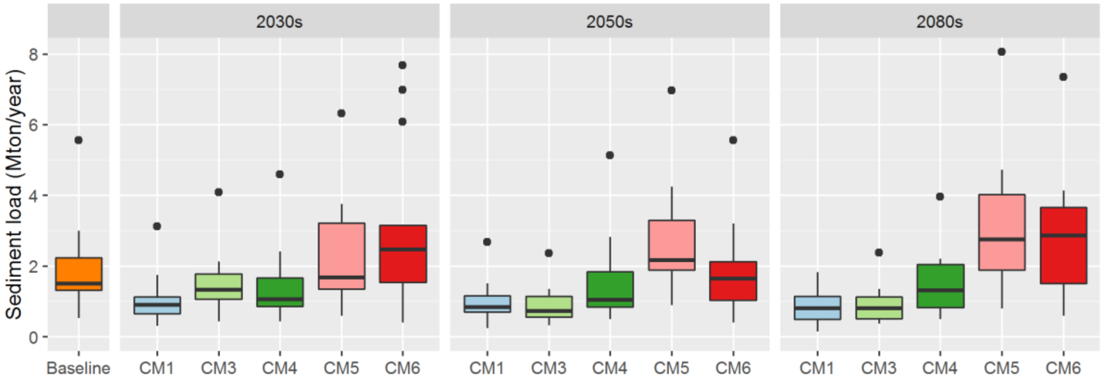

Figure 12 Boxplots of annual average sediment load at watershed outlet (Thika/Chania) under baseline conditions and different climate change scenarios

Figure 13 and Figure 14 shows a map of the change in erosion rate that is predicted by respectively the RCP 4.5 and RCP 8.5 scenarios. This map shows the difference between the erosion simulated for baseline conditions and the mean erosion rate computed for the RCP 4.5 and RCP 8.5 scenarios (excluding CM2). The RCP 4.5 projections predict an overall decrease in erosion rates, primarily on the steep coffee-cultivated slopes. The decrease is related to the fact that the RCP4.5 projections generally predict a decrease in rainfall, especially relevant during the rainy season. However, for the RCP 8.5 scenarios, an increase in erosion rates are predicted. Also here the steep coffee-cultivated slopes are mostly affected, but also the agricultural area at the upstream end of the watershed, with a more heterogeneous cropping pattern.

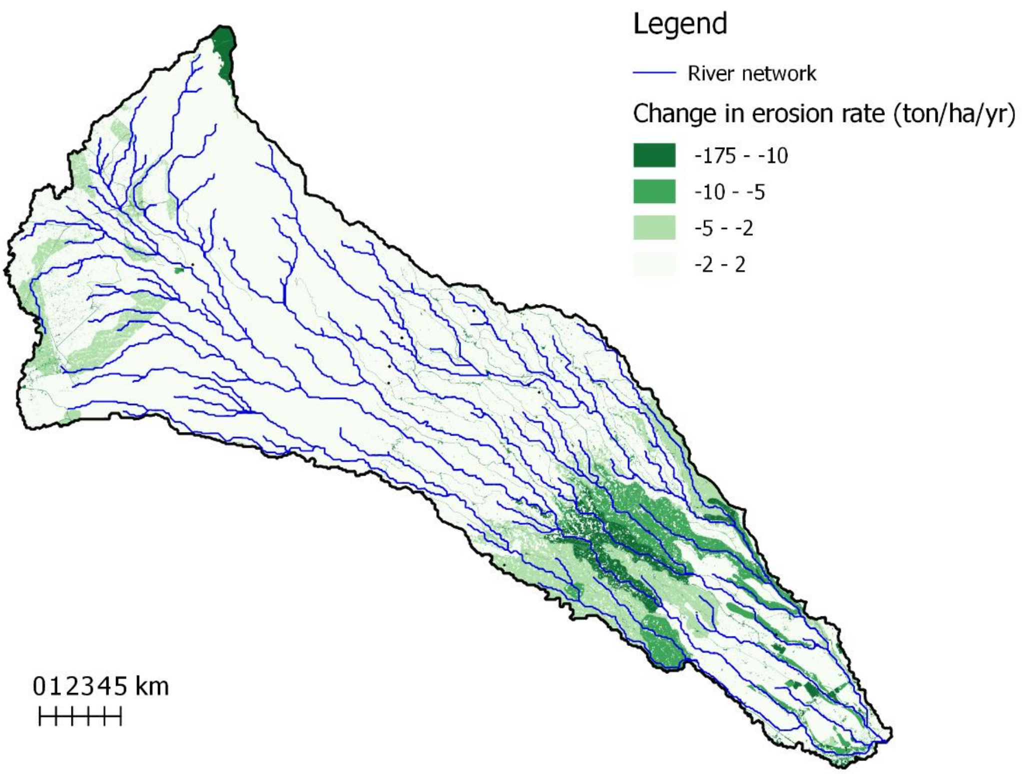

Figure 13 Changes in erosion rate in Thika/Chania watershed due to climate change in 2076 - 2095: average of RCP 4.5 scenarios versus baseline conditions.

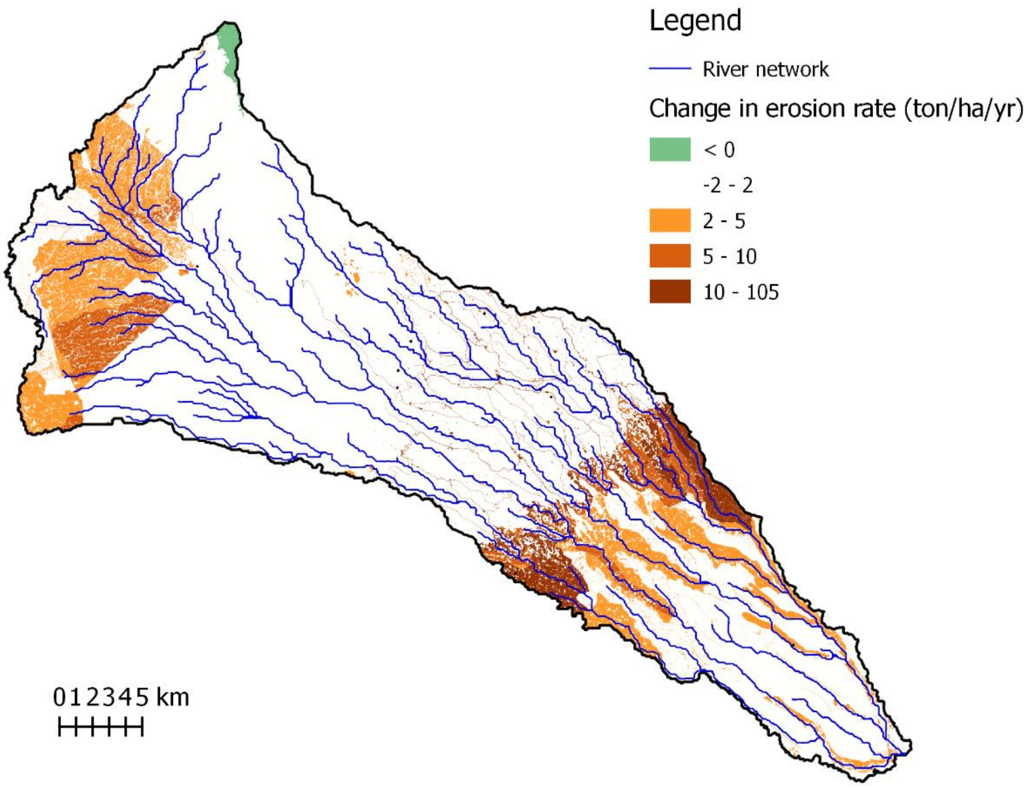

Figure 14 Changes in erosion rate in Thika/Chania watershed due to climate change in 2076 - 2095: average of RCP 8.5 scenarios (excluding CM2) versus baseline conditions.

3.3 Climate change impacts and sustainable land management

Climate change affects flows and sediment budgets in the basin, and thus also the impacts of interventions, measures and investments in the basin. The currently operational Nairobi Water Fund is involving a large group of smallholders and giving them incentives to enhance their practices in order to improve water quantity and quality downstream. The downstream impact of improved upstream land management will depend on the hydrologic response of the basin, and thus on the climate. Changes in rainfall and temperature will have an impact on the water availability, erosion and water quality. Thus, climate change will affect the effectiveness of these investments.

The targeted investment portfolio of the Nairobi Water Fund involves a mix of activities that were selected based on consultations with the Steering Committee of the Fund, local extension services, and other experts during the starting phase of the Business Case study. These activities were prioritized according to biophysical and socio-economic criteria (see for more details [*Vogl et al.*, 2016]) and for different investment portfolios. This study will analyze the targeted 10 million USD investment portfolio that included the following activities:

- Riparian management: a collection of activities to protect the riverine zone
- Agroforestry: a conversion of part of the crop lands to agroforestry
- Terracing: implementation of fanya juu or bench terraces on the steeper slopes
- Reforestation: a conversion of croplands to forest
- Grass strips: the planting of grass strips along the contours of the crop lands.
- Road mitigation: different activities to reduce runoff and erosion from roads

The impact of investment on sediment loads in the watershed under different climate scenarios is summarized in Table 7, for the different periods and projections. The table compares a Business-As-Usual (BAU) scenario (no land use change or interventions – as in the previous sections), compared to the watershed with the full implementation of the Water Fund investment portfolio (targeted at 10 million USD). The relative changes in the table are calculated by comparing them to the current climate and the Business-As-Usual scenario.

Table 7 **Total sediment load of the Thika/Chania watershed: the absolute values and relative difference (%) compared to current climate and business-as-usual for different projections and periods, with and without investments in sustainable land management**

Scenario / Period	Baseline	CM1	CM3	CM4	CM5	CM6	All proj.
Business-As-Usual							
Current	1.9 (0)						
2030s		1.0 (-45)	1.5 (-22)	1.5 (-23)	2.3 (21)	3.0 (60)	1.9 (-2)
2050s		1.0 (-48)	0.9 (-52)	1.6 (-14)	2.7 (44)	1.9 (-1)	1.6 (-14)
2080s		0.9 (-54)	0.9 (-53)	1.5 (-23)	3.1 (62)	2.8 (47)	1.8 (-4)
Investments in sustainable land management							
Current	1.2 (-39)						
2030s		0.6 (-69)	0.9 (-55)	0.9 (-54)	1.4 (-25)	1.8 (-3)	1.1 (-41)
2050s		0.5 (-72)	0.5 (-73)	1.0 (-49)	1.7 (-11)	1.1 (-41)	1.0 (-49)
2080s		0.5 (-76)	0.5 (-73)	0.9 (-54)	1.9 (0)	1.7 (-11)	1.1 (-43)

From the table it is clear that, independent of the climate projection, the investment scenario effectively reduces sediment load. Reduction of around 40-50% are predicted by the model, and based on the assumptions discussed earlier. Another important observation is that for all climate projections, sediment loads after investment are below the current value (1.9 Mton/yr). Even for the wettest projection (CM6), the investments will cause a decrease in sediment load (e.g. -3% for the 2030s). In other words: under climate change, investing in the watershed will cause a significant decrease in sediment load.

At the same time, from Table **7** it becomes evident that the cost-effectiveness of the investments and activities can be considerably influenced by climate change, either positively or negatively – depending on the projection considered. Overall, the reductions under the climate change projections and for the different future periods are slightly higher (between -41% and -49%) than the reductions predicted under the current climate (-39%).

Figure 15 shows the interannual variability in the annual sediment loads for the Thika/Chania watershed. This figure is similar to Figure 12, but showing the land management scenario instead of the BAU scenario. The orange Baseline box on the left shows the interannual variability of sediment load from the baseline SWAT simulations, for comparison. This figure also shows that generally sediment loads will decrease under the investment scenario, compared to the BAU scenario. In fact, all annual values in the climate projections are below the maximum annual value in the baseline (BAU/Current climate), as can be seen from the dots in this figure (values that are outside the interquartile range).

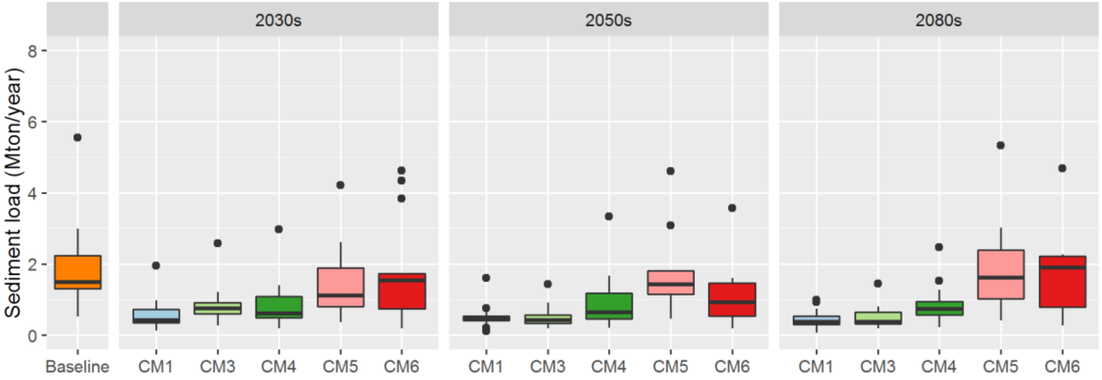

Figure 15 Annual sediment load for the land management scenario, for the different periods and climate projections.

The changes in erosion and sediment load are driven by changes in fast runoff on the land. Fast runoff can be reduced considerably when implementing sustainable land management practices. Flows in the river will also change, although less drastically, as was shown by the Business-Case study on the Water Fund. The changed land use practices (considering the assumptions on adoption of the practices) reduce peak flows, and enhance baseflow slightly. They also reduce non-productive evaporation from the cropped areas, which leads potentially to an overall increase of streamflow of 4% in this watershed.

This analysis shows (see Table 8) that climate change impacts on flows are much higher. In the BAU scenarios, mean annual flow changes range between -40% and +40%. In other words, the impacts of climate change on flows are considerably more important than the changes caused by the land management interventions. Figure 16 shows the monthly impacts, instead of the mean annual flows, and compared to the baseline. The figure demonstrates that flows in the rainy periods can be more than halved for certain climate projections. Flows in the dry periods generally decrease.

In a scenario where water availability reduces drastically both for farmers as well as for downstream users, it can be expected that land use, farmers´ practices, cropping patterns, etc will change: this is effect not included in the modeling study. Continuous monitoring of the socio-economic situation, behavior change as well as hydrological monitoring is thus crucial, to measure the effectiveness of the investments.

Table 8 Mean streamflow: absolute values and difference (%) compared to Current climate and BAU, for different projections and periods, with and without investments in sustainable land management

Scenario / Period	Current	CM1	CM3	CM4	CM5	CM6	All proj.
Business-As-Usual (BAU)							
Baseline	16 (0)						
2030s		9 (-40)	14 (-10)	14 (-14)	14 (-7)	20 (27)	14 (-9)
2050s		10 (-34)	11 (-33)	14 (-12)	19 (23)	14 (-12)	14 (-14)
2080s		9 (-40)	10 (-35)	14 (-12)	22 (40)	20 (30)	15 (-3)
Investments in sustainable land management							
Baseline	16 (4)						
2030s		9 (-37)	14 (-7)	13 (-10)	14 (-4)	20 (31)	14 (-5)
2050s		10 (-31)	10 (-29)	14 (-9)	19 (26)	14 (-9)	13 (-10)
2080s		9 (-36)	10 (-32)	14 (-9)	22 (44)	20 (33)	15 (0)

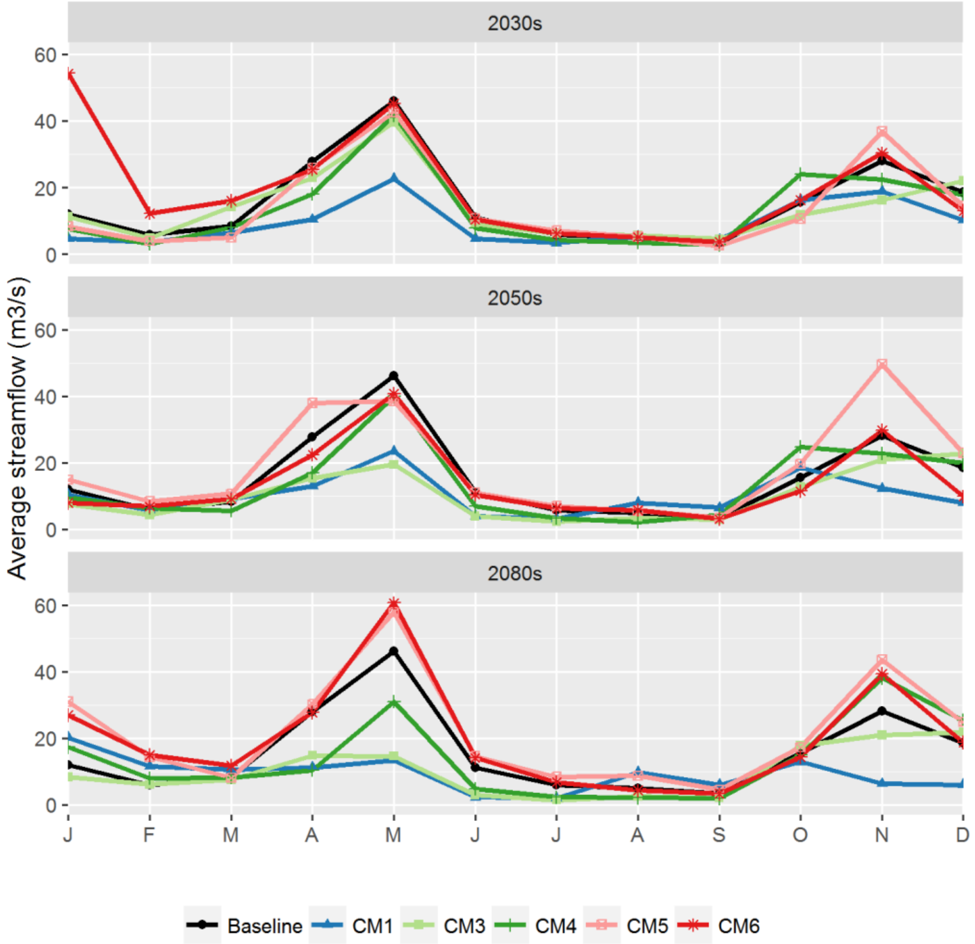

Figure 16 Monthly streamflow patterns at the basin outlet, for different periods and climate projections, for the sustainable land management scenario

3.4 Climate change impacts on reservoir sediment budget

3.4.1 Business-as-usual for Masinga sediment inflow

The annual sediment yield predictions of the Thika/Chania catchment were upscaled to the entire Upper Tana (Masinga) by multiplying each value with the relative contribution of Thika/Chania to the basin yield of 8.0 Mtons/yr. The mean annual sediment of Thika/Chania is 1.9 Mton/year (see Table 6). Thus, each annual value of the simulations was multiplied with 8.0/1.9 = 4.2. Expressed in an equation:

$$SYLD_{MAS,y} = \frac{\widehat{SYLD}_{MAS,0}}{\widehat{SYLD}_{TC,0}} SYLD_{TC,y}$$

in which $SYLD_{MAS,y}$ is the sediment yield for Masinga for a certain year, $SYLD_{MAS,0}$ is the mean sediment yield under current conditions entering Masinga (8.0 Mtons/year), $SYLD_{MAS,0}$ is the mean sediment yield of Thika/Chania (1.9 Mtons/year – from simulations), and $SYLD_{TC,y}$ is the simulated annual sediment yield of Thika/Chania. Figure 17 shows the interannual variability of sediment inflow into the Masinga reservoir, using the upscaling method mentioned. These data will be used in a follow-up study on hydropower impacts in the Masinga dam, carried out by the WISE-UP partner Manchester University.

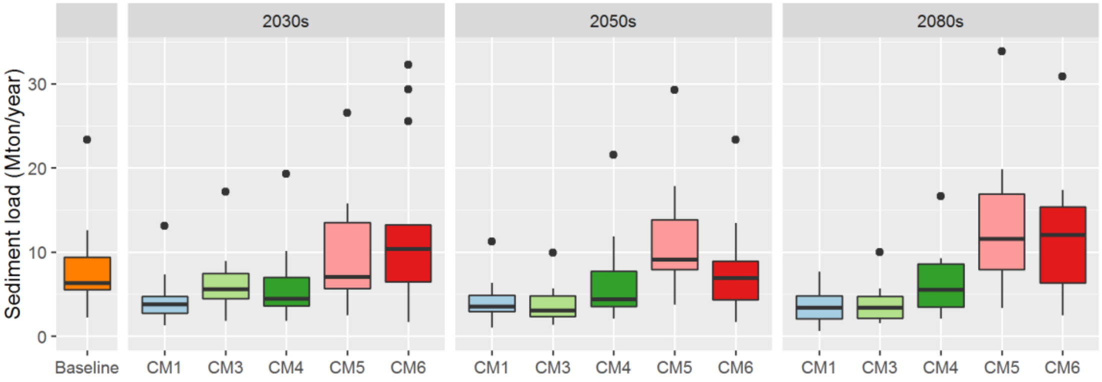

Figure 17 Boxplot showing annual variability under climate change, of Masinga sediment inflow, compared to baseline (current climate)

3.4.2 Investments in Thika/Chania – impacts on Masinga sediment inflow

To assess how the investment scenario influences the sediment yield entering the Masinga reservoir, it was assumed that the rest of the Upper Tana develops "Business-as-Usual", while in the Thika/Chania watershed, investments lead to certain reductions of the sediment yield. The calculation was done as follows:

$$SYLD^{inv}{}_{MAS,y} = SYLD_{MAS,y} - (SYLD_{TC,y} - SYLD^{inv}{}_{TC,y})$$

in which the superscript "*inv*" refers to the annual values under the investment scenario.

Figure 18 shows the interannual variability of sediment inflow into the Masinga reservoir under the sustainable investment scenario. Also these data will be further analyzed in the water resources and hydropower assessment tool, in the follow-up study by Manchester University.

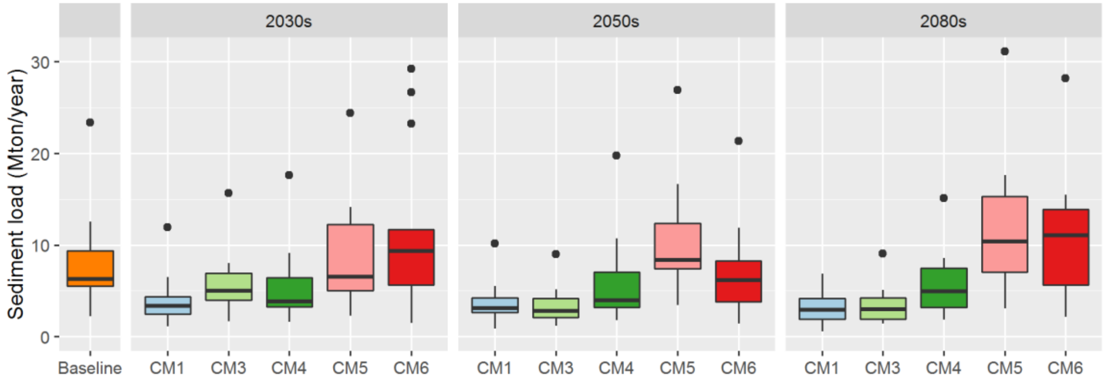

Figure 18 Boxplot showing annual variability under climate change, of Masinga sediment inflow after investing in Thika/Chania watershed, compared to baseline (current climate, no investment)

3.4.3 *Investment in all priority watersheds - impacts on Masinga sediment inflow*

The Nairobi Water Fund business case also envisaged investments in other priority watersheds in the Upper Tana basin, besides the Thika/Chania. These other watersheds (Maragua and Sagana) were not simulated for this climate change study. However, to obtain an approximate estimate of how these investments and climate change influence the sediment inflow into Masinga, the assumption was made that the reduction of sediment yield under climate change is proportional to the reduction under the current climate. Thus:

$$SYLD^{inv}{}_{MAS,y} = SYLD_{MAS,y} - \frac{\Delta\widehat{SYLD}_{all,0}}{\Delta\widehat{SYLD}_{TC,0}} * \left(SYLD_{TC,y} - SYLD^{inv}{}_{TC,y}\right)$$

in which the $\Delta SYLD_{all,0}$ refers to the difference between the total sediment load of all priority watersheds under the BAU scenario, and the investment scenario, under the current climate. $\Delta SYLD_{TC,0}$ the same but for Thika/Chania. The below figure shows the interannual variability, which will be further studied in the follow-up study on hydropower.

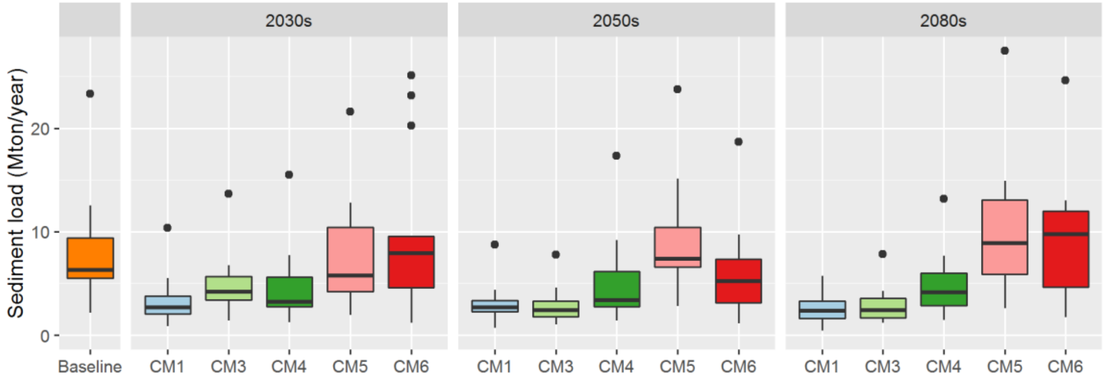

Figure 19 Boxplot showing annual variability under climate change, of Masinga sediment inflow after investing in all priority watersheds of Upper Tana, compared to baseline (current climate, no investment)

3.4.4 Masinga reservoir capacity under the different future scenarios

The Masinga reservoir capacity for the different periods and climate projections were calculated using the assumptions taken from the bathymetric survey study in 2010/2011 [*Hunink and Droogers*, 2011]:

- In 2010, Masinga capacity was estimated to be 1402 MCM. For simplicity, it was assumed that all scenarios apply from this year onwards.
- Masinga traps 99% of all sediment flowing into the reservoir
- A specific weight of 1.237 ton/m3 for the sediment inflowing into the reservoir, including the effect of sediment consolidation
- The calculations are done for the mid-point of each period (2035, 2055, 2085 resp.)

Table 9 shows the storage capacity for Masinga reservoir, for the different future periods and climate projections, using the upscaling approach as presented before.

Table 9 Storage capacity of Masinga reservoir (MCM) for the different future periods and climate projections

Climate model	**Period**	**Business As Usual**	**Investments in Thika/Chania**	**Investments in all priority watersheds**
Baseline	2010	1402	1402	1402
CM1	2030s	1314	1323	1335
CM1	2050s	1253	1269	1291
CM1	2080s	1180	1205	1240
CM2	2030s	1207	1226	1252
CM2	2050s	1079	1112	1157
CM2	2080s	620	701	810
CM3	2030s	1278	1290	1307
CM3	2050s	1264	1278	1297
CM3	2080s	1176	1198	1229
CM4	2030s	1278	1290	1306
CM4	2050s	1155	1179	1211
CM4	2080s	1030	1066	1115
CM5	2030s	1208	1226	1250
CM5	2050s	988	1025	1076
CM5	2080s	625	695	789
CM6	2030s	1146	1170	1202
CM6	2050s	1115	1143	1180
CM6	2080s	698	764	852

4 Conclusions

Climate change will affect water resources, sediment budgets and ecosystem services of the Upper Tana basin. Nowadays, this basin provides critical services to society (agriculture, water supply and hydropower) and sustains important biodiversity hotspots. An analysis was carried out of climate change impacts on water fluxes and sediment yields in one of the most important sub-watersheds of the basin. The analysis was carried out for the Thika/Chania watershed. The outcomes show that:

1. Climate change considerably affects the water balance: the simulations show that evapotranspiration (directly related to crop production and biodiversity) can either increase or decrease; overall the trend is slightly negative
2. Impacts on flows and sediment are considerable, but very much dependent on the climate model projection. Overall there is a negative trend concerning flows. Reduced flows during the wet season cause also a reduction in sediment yield (in some projections about 50% of the current baseline values) and sediment concentrations. However, some projections predict considerable increases in sediment loads (up to 60% increase), with a high increase in interannual variability.
3. The impacts of climate change on the Water Fund investment portfolio were analyzed, showing that also under climate change the activities result in a notable positive change for downstream services and users. Under climate change, the improved land management practices still lead to a reduction in runoff and erosion, causing considerable reductions in sediment loads potentially harming downstream water users. Still, impacts differ considerably among the projections as they are very much dependent on the future water balance of the watershed. Overall, the relative impact of the investment portfolio under climate change was similar to what was predicted under the current climate (about 40% less sediment yield from the Thika/Chania watershed).
4. The range of impacts on water availability for downstream users and streamflow that can be expected due to climate change is much higher than the impact caused by the Water Fund investment portfolio. This stresses the need for continuous monitoring of streamflow and understanding the underlying causes of future changes, to assess whether they can be attributed to climate change or land use and management change.

Overall, this study stresses the importance of taking into account climate change impacts when evaluating ecosystem services in a complex basin with critical links between upstream land management and downstream water use, like the Upper Tana basin. The results of this study will be used in subsequent analysis within the WISE-UP project, which should lead to more insights on climate change impacts and ecosystem services in the Upper Tana.

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