Impact Assessment of Investment Portfolios for Business Case Development of the Nairobi Water Fund in the Upper Tana River, Kenya

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Preface

After having launched successfully several Water Funds in Latin America and the United States, The Nature Conservancy (TNC) has started working in 2011 to launch the first Water Fund in Africa to restore and protect the condition of the Upper Tana River, Kenya, and improve Nairobi's water security. The goal is to engage downstream users, corporations and utilities to willingly contribute to a water conservation fund that supports water protection activities, such as changing agricultural practices to reduce erosion.

In 2013, a Business Case study was started for the Nairobi Water Fund to evaluate the return on investment of different investment portfolios across the catchment and to quantify impacts and benefits for the different users. The Business Case study is carried out by a large consortium consisting of experts of TNC, Stanford University (Natural Capital Project), the International Center for Tropical Agriculture (CIAT) and FutureWater.

FutureWater´s role in the Business Case study is to carry out the biophysical modelling assessment, analysing the impacts of the investment portfolios and interventions in the Upper Tana catchment. The analysis provides biophysical outputs at the different service points of interest for the Water Fund and an analysis of the upstream economic benefits. This report is the complete description of these activities and is added as an appendix to the full business case report [*TNC*, 2015].

Summary

Ecosystem services of the Upper Tana Basin are currently undervalued and under increasing threat from climate change and increasing intensity of land use. Current land use practices, dominated by small holder farmers, are leading to loss of riparian zones and valuable topsoil which reduces farm productivity while resulting in increased suspended sediment in rivers during storm events as well as occasional landslides. This causes Nairobi citizens and downstream businesses that depend on a reliable and clear water supply to be increasingly vulnerable.

Given the these challenges, TNC is applying its tested, sustainable and long term payment for ecosystem services methodology that it has used in Latin America, and is developing the Nairobi Water Fund. This work is part of the Business Case study that was started for the Water Fund in 2013. This report summarizes results of the biophysical impact assessment to support the Business Case study of the Water Fund. SWAT was used to convert the outcomes and investment portfolios of the RIOS tool (analyzed by experts of the Natural Capital Project "NatCap") into quantifiable impacts (erosion, turbidity, flows).

The results show significant erosion reductions in the agricultural areas, mainly for the coffee areas and the degraded land areas. For the unpaved roads, also significant reductions in erosion are expected. In general significant reductions in erosion can be achieved in many points across the watersheds by implementing a mix of activities. Significant economic benefits can be expected for the upstream agricultural areas, besides the economic benefits for downstream water users (the latter included in the main business case report [*TNC*, 2015]. Especially in the coffee zones the benefits will be considerable, but also in the general agricultural areas economic output will increase substantially.

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1 Introduction

1.1 Background

The Nature Conservancy (TNC) has successfully established several Water Funds in Latin America and the United States that are helping protect water sources for millions of people. These Water Funds function like endowments: they are capitalized to a sufficient level to generate substantial earnings annually, which are then disbursed for conservation, ensuring a sustainable revenue stream.

Figure 1-1. The Nairobi Upper Tana Water Fund: protecting water sources for an environmentally sustainable watershed and secure water supply

Water Funds typically engage large, downstream users, corporations and utilities that willingly contribute to a water conservation fund as a way of shoring up their business investments. Water Funds make a variety of water protection activities possible, such as changing agricultural practices to reduce erosion and providing micro-finance for livelihoods that reduce deforestation pressure.

In 2011 TNC has started working with local partners to launch the first Water Fund in Africa to restore and protect the condition of the Upper Tana River and improve Nairobi's water security. First a formal scoping study was carried out to determine the potential for Water Fund support and development in the Tana River catchment, Kenya. Among the many aspects of the scoping study was outreach to the Green Water Credits (GWC) program [*Kauffman et al.*, 2007, 2014; *Hunink et al.*, 2012b].

In 2012 TNC launched demonstration projects in three priority watersheds – Maragua, Sagana and Thika/Chania of the Upper Tana basin, all of which are important for Nairobi's water and power supplies. The Nairobi Water Fund has started to implement environmental and socio-economic monitoring programs and has a fully functioning 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).

1.2 Objectives

In 2013, a Business Case study was started for the Nairobi Upper Tana Water Fund. This study evaluates the return on investment of different investment portfolios across the catchment and quantifies impacts and benefits for the different users. Key questions that are answered during this study are “Where and in what activities should the fund invest its money?” and “What will be returns on that investment, in terms of improved agricultural production, reduced sediment loads, and the value accrued to major fund partners like KENGEN and Nairobi Water Supply?” The Business Case study is carried out by a large consortium consisting of experts of TNC, Stanford University (Natural Capital Project), CIAT and FutureWater.

FutureWater´s role in the Business Case study is to carry out the biophysical modelling assessment, analyzing the impacts of the investment portfolios and interventions in the Upper Tana catchment. The analysis provides biophysical outputs at the different service points of interest for the Water Fund. Based on the biophysical modelling, an analysis of the upstream economic benefits is carried out and described in this report, feeding in the overall return on investment (ROI) analysis of the Business Case study.

1.3 Biophysical setting

The Tana River is Kenya’s longest river, stretching almost 1,000 kilometers from the edge of the Great Rift Valley to the fertile delta where it meets the Indian Ocean. The river basin covers approximately 17,000 km^2 with about 5.3 million inhabitants. The Tana River basin includes two of Kenya’s five “water towers”: the Aberdare Mountains and Mount Kenya. These water towers are in the upper part of the Tana River, also called the Upper Tana basin. This basin sustains important aquatic biodiversity and drives agricultural activities that feed millions of Kenyans.

The Upper Tana basin (9,411 km^2 above Kamburu dam) is a relatively humid basin with average annual rainfall amounts of about 2000 mm at higher altitudes, drier conditions (about 500 mm per year) at lower elevations, and annual potential evapotranspiration rates of around 1000 mm (Figure 1-2). There are two wet seasons and two dry seasons as a result of the monsoon. Approximately half of the annual rainfall in the basin falls from mid-March to June, known as the long rains. The so-called short rains are between October and December when the area receives approximately a third of its annual rainfall.

The main rivers of the Upper Tana river basin include the Chania, Thika, Sabasaba, Maragua, Mathioya, Sagana, Gura and Amboni. The rivers flow through deep valleys as they cut through the forests, tea and coffee zones into the lower semi-arid areas of the catchment. The upstream non-cultivated areas have a variety of vegetation which includes the closed canopy forest, bamboo zone, sub-alpine and alpine vegetation.

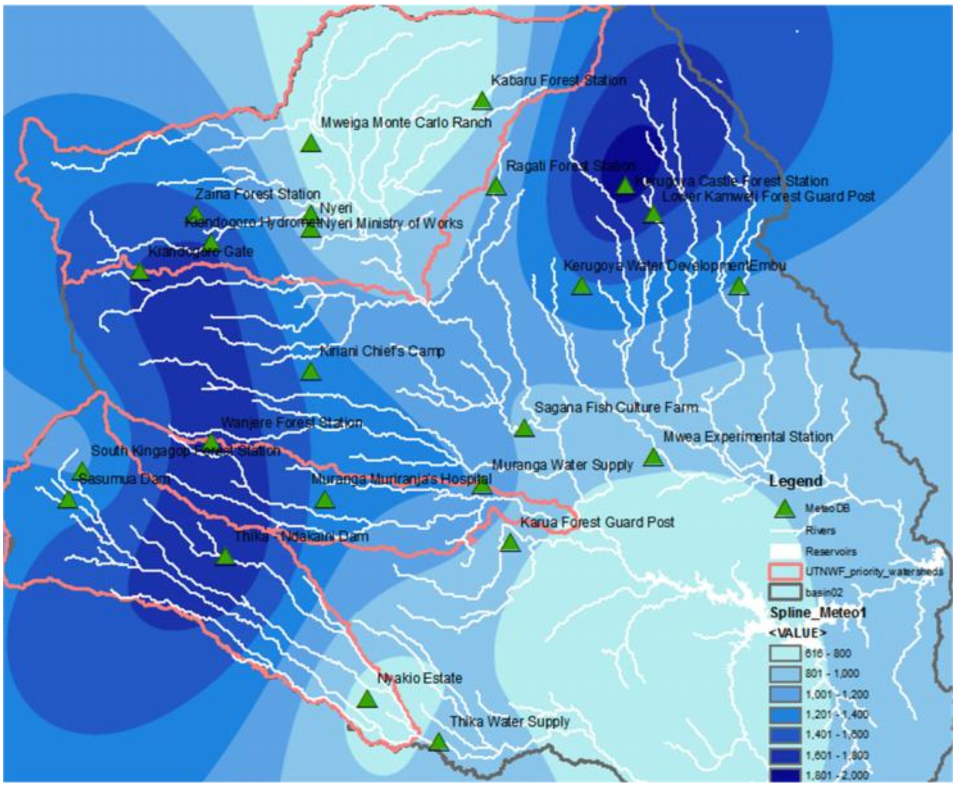

Figure 1-2. Mean annual precipitation of the Upper Tana basin

During recent decades, the population in the higher mountain areas has increased, former wetlands, floodplains and riparian areas have been converted into small holder agricultural land. Rainfed subsistence agriculture now constitutes over 60% of the land use. The main rainfed crops are maize, coffee and tea, principally cultivated in the higher and wetter areas of the basin where crop rotation is common. At lower altitudes, irrigated crops (flowers, fruit and vegetables) are produced for the national and international market.

1.4 Major water uses and users

1.4.1 Water use

The ecosystem services provided by the Upper Tana River basin are of key importance for the Kenyan economy and environment. The basin is the most productive basin in terms of agriculture of Kenya, provides the major share of the total hydropower production of the country, and provides 90% of the total urban water supply to the capital Nairobi.

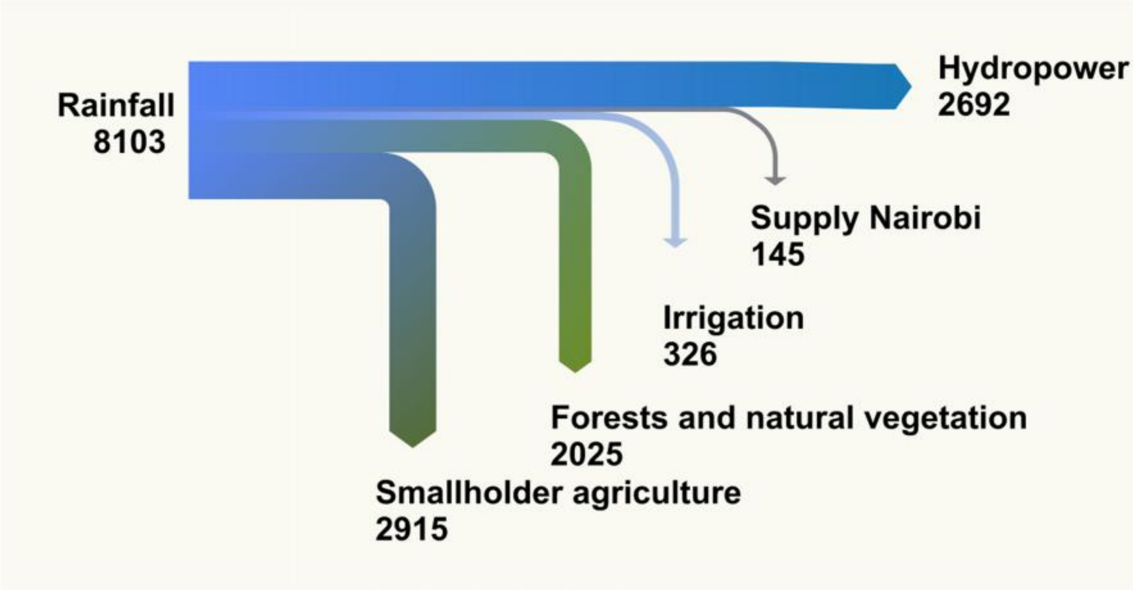

Figure 1-3 shows the water use of the principal users that rely on the basin water resources upstream of Kamburu dam. As can be seen, a major water user is rainfed agriculture, using on average 2915 million cubic meters (MCM) per year of the total 8102 MCM coming in from rainfall. The biggest part of this water use is transpired through the crop. Natural vegetation including forests uses also a major share of the total water resources in the basin, around 2025 MCM per year. Another major (non-consumptive) water user is hydropower that uses on average around 2836 MCM a year for power production. Irrigated agriculture receives around 326 MCM a year, while around 145 MCM is abstracted from the basin for Nairobi city water supply annually.

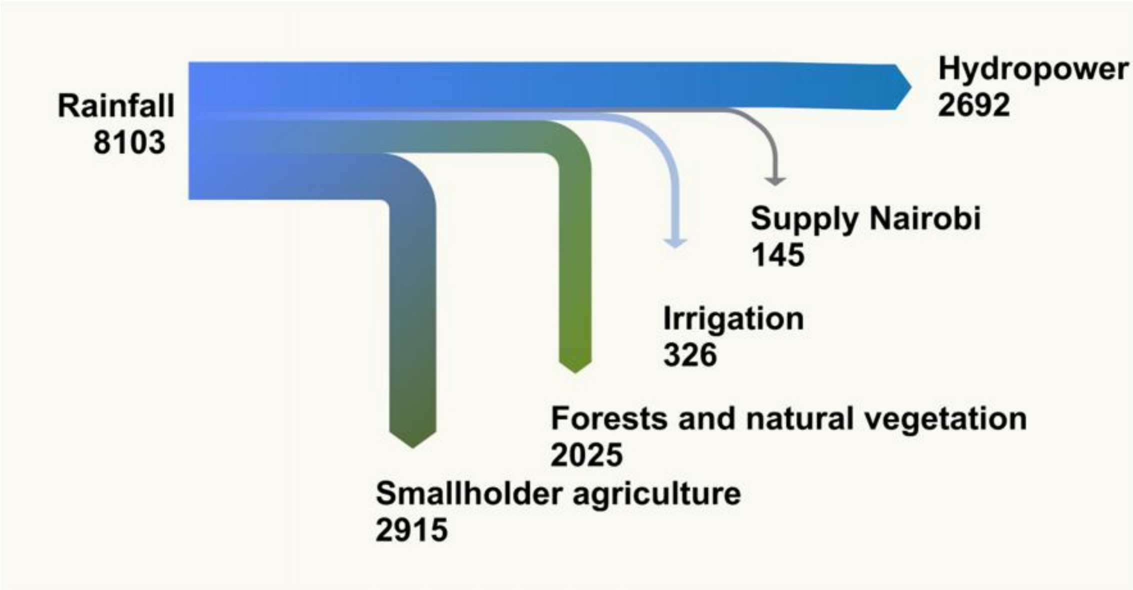
Rainfall
8103
Hydropower
2692
Supply Nairobi
145
Irrigation
326
Forests and natural vegetation
2025
Smallholder agriculture
2915

Figure 1-3. Annual water use (MCM) of the principal users relying on the water supply of the Upper Tana River basin above Masinga dam (based on data from [*Hunink and Droogers*, 2011] **)**

Nairobi City Water and Sewerage Company (NCWSC) is the major water and sewerage service provider for Nairobi. It was established in 2002 and is owned 100% by county government of

Nairobi. The Company is private and has an independent Board of Directors. They are a member of the Water Fund Secretariat and will also undertake watershed management actions.

KenGen is the leading electric power generation company in Kenya, producing about 80% of electricity consumed in the country. The company utilizes various sources to generate electricity ranging from hydro, geothermal, thermal and wind. Hydro is the leading source, with an installed capacity of 767 MW, which is 65% of the company's installed capacity. KenGen is a member of the Water Fund Secretariat.

The Water Resources Management Authority (WRMA) was created on 2003 following the enactment of the Kenya Water Act (2002) that allowed decentralized management of water services. It is a government entity under the Ministry of Environment, Water and Natural Resources, charged with being the lead agency in water resources management. The Authority's function is to develop principles, guidelines and procedures for the allocation of water resources; monitor water use; manage and protect water catchments; gather and maintain information on water resources; and liaise with other bodies for the better regulation and management of water resources. WRMA has a workforce of about 700 with about 95 working in Tana Watershed. These are based at the Tana regional office in Embu and in the 6 sub-regional offices. They are the key partner that will provide overall regulatory authority and policy support. WRMA will also be responsible for project monitoring and assisting with the implementation of the new interactive and live data management system for the river. They are members of the Water Fund Secretariat.

1.4.2 Infrastructure

The Upper Tana basin supplies Nairobi city water through the Sasumua and Ndakaini dams drawing water from the Chania and Thika rivers respectively (Figure 1-4). The physiographic survey study [*Z&A*, 2011] estimated the full reservoir volume for the Ndakaini dam at 71.5 Mm3 and for the Sasumua dam 4.9 Mm3. A few other small dams exist throughout the basin used for either local water supply (domestic or irrigation) or small hydropower facilities. Downstream in the basin are the main hydropower reservoirs, Masinga and Kamburu.

Figure 1-4. Satellite image of Sasumua and Ndakaini dam (source: Google Earth)

According to data provided by the NCWSC, the withdrawals from Ndakaini and Sasumua dam are relatively constant along the year without a clear seasonal trend, with only minor variations when water availability is low. For the Sasumua dam, the average extraction rate is 58,000 m3/day. The water abstracted from the Thika dam is first transferred to the Chania catchment.

On its way, this transfer also captures water from the Kiama River and the Kimakia River. On average. Downstream of the outfall of this transfer, water is abstracted at the Mwagu weir (Figure 1-5) to be diverted to the Ngethu treatment plant.

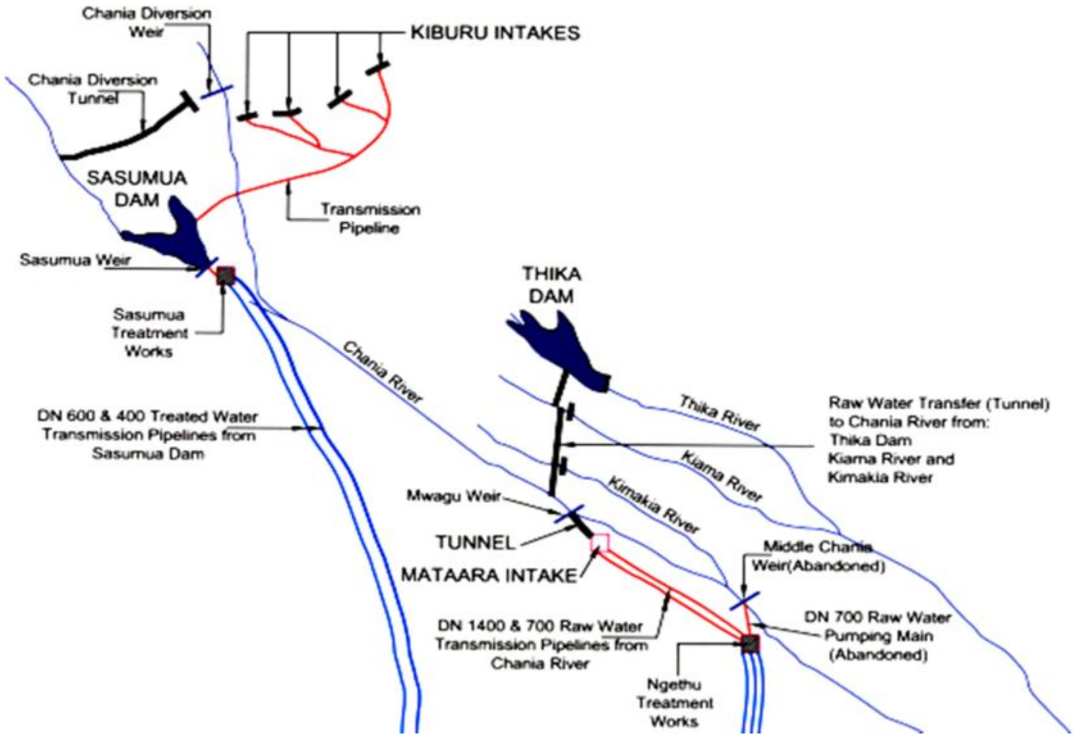

Figure 1-5. Diversions from the Upper Tana catchment related to Nairobi Water Supply (source: NCWSC)

A large list of additional mostly small storage dams were proposed in a recent WRMA study [*Z&A*, 2011]. They concern 96 potential reservoir locations spread out all over the Upper Tana [*Z&A*, 2011]. There is no good information available on these projects, and the current status of these plans is not clear. However, their construction could significantly alter the hydrologic regime of the Upper Tana, as well as the sediment yields [*Z&A*, 2011].

Another relevant infrastructural project being planned to be built is a new water transfer from the Maragua catchment to the NCWSC facilities. This makes the Maragua watershed of key importance for future investments in sustainable watershed management activities.

Upstream of the Masinga reservoir, there are multiple small hydropower facilities, including the Tana power station (20 MW), Sagana power station (1.5 MW), Ndula power station (2.0 MW), Mesco power station (0.5 MW), and Wanji power station (7.4 MW). While their contribution to energy production along the Tana River is modest, sedimentation at the dams for these power stations may also be an issue.

1.5 Issues addressed by the Water Fund

1.5.1 Context

The Green Water Credits studies, the scoping study and surveys carried out by TNC provided good insight in the challenges that are faced for the Water Fund. These analyses demonstrate a clear degradation of the watershed, and considerable issues to tackle. Since the 1970s, large areas of forests were replaced by agricultural fields. There is increasing demand for irrigation water on the slopes of Mount Kenya, particularly to support horticulture production. But water usage affects water availability in lower lying, drier areas. Encroachment is happening rapidly on natural wetlands that earlier stored runoff water, recharged aquifers, and produced valuable biodiversity. This encroachment, landslides, degradation and subsequent siltation and pollution of spring heads is contributing to increased erosion. One of the downstream effects of erosion is sediment deposition in reservoirs.

The socio-economic survey carried out by TNC in 2013 [*Leisher*, 2013] confirmed that most residents in the upper watershed rely on agriculture as their main source of income. Only 23% of residents were food secure year round. 32% of people in the upper watershed irrigate during the dry season and 77% of residents said erosion occurs on their land. 54% had 25% or less of their land under soil conservation measures. Terracing and grass strips were the most common soil conservation measures. 53% of farms have declining vegetation cover compared to five years ago, and 79% of residents say the color of the local river after a rain is a higher intensity now than five years ago, suggesting that soil erosion is increasing. 45% said it takes more than one month for the color of the local river water to clear after a rain. While the land and water issues in the study area are substantial, 93% of people said they would be interested in joining a land and water conservation project.

Increasing suspended sediment in the river has become a major issue as it increases maintenance and treatment costs, and reduces the likely useful life of reservoirs due to siltation. City residents characteristically get water once a week while corporate customers have to endure water rationing schedules during the regular drought periods. Today, 60% of Nairobi's residents are water insecure and Nairobi's water shortages will only worsen, as the city's population is one of the fastest growing on the continent, with an annual growth rate of 2.8%[1]. The treatment and distribution facilities are not adequate to meet the current or growing water demands of the city's residents and businesses.

The current water deficit for the city stands at 168,000m3 per day (or 30% of demand) when the system is operating at full capacity. Departures from normal operating conditions are becoming more common as the population grows and sediment runoff is polluting the streams and rivers of this critical watershed. Figure 1-6 shows the trend of increasing turbidity measured at Nairobi's primary water intake. Nairobi Water Company reports that water treatment costs often increase by more than 33% as sediment runoff, which can be prevented through improved land management, fills and chokes treatment equipment during the wet season, further worsening supply interruptions.

[1] Nairobi UrbanSector Profile, UN Habitat, 2006.

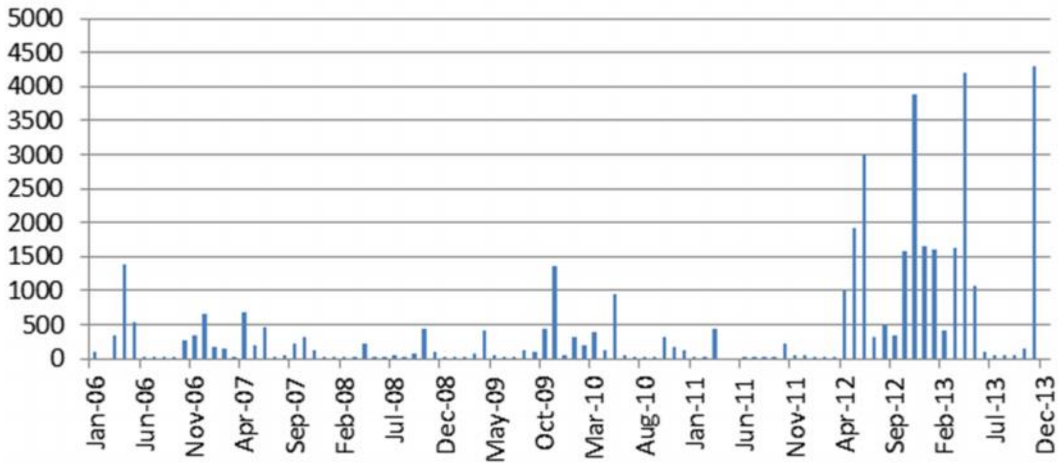

Figure 1-6. Maximum turbidity levels measured at the main intake for Nairobi's water treatment facility between January 2006 and October 2013.

The Upper Tana basin also feeds a cascade of five hydropower dams that supply about half of Kenya's electricity. Increasing sediment loads and declining dry season flows are an issue here as well; filling reservoirs and reducing water storage capacity and power production, particularly during the dry season when power needs are greatest. Hydropower capacity and costs are also impacted by increasing sedimentation.

The rivers that contribute most to the Upper Tana sediment load are those that drain the densely populated, intensively cultivated tropical foothills zone. These sub-basins have a flashy hydrological response and an almost instantaneous response of flow to rainfall. Also several studies [*Brown and Schneider*, 1996; *Z&A*, 2011] confirm the importance of unpaved roads and tracks to the total sediment load of the Upper Tana, although hardly any quantitative figures are available for this process.

In short, the Tana River, while providing 90% of Nairobi's water and 50% of Kenya's hydropower, is undervalued by local residents who receive no outside investment or incentives for protecting this critical resource. By creating a self-sustaining, well-managed Upper Tana Water Fund to oversee inputs to manage this resource, creating a mechanism to invest in watershed management, and improving understanding of the value of the resource and what investment is required to protect this resource, behaviour change and management change in the Upper Tana River Watershed should be incentivized.

1.5.2 Erosion and sediment problems

Previous studies on erosion in the Upper Tana basin have provided some estimates on the erosion rates and the related problems. Table 1-1 shows a list of publications and studies on erosion in the Upper Tana catchment and in similar areas that are relevant for the business case modelling assessment.

Table 1-1. Studies and data on erosion in the Upper Tana catchment (chronological order)

Reference	Study area	Focus
Dunne [1979]	Tana and other African basins	Comparative study on erosion and sediment yield
Ongwenyi et al [1993]	Kenya	Overview of data and estimates on

		erosion in Kenya
Brown et al [1996]	Upper Tana, Kenya	Basin-wide assessment using field data
Mati et al. [2000]	Upper Ewaso Ng'iro North	Regional assessment compared with field data of erosion.
Owino and Gretzmacher [2002]	Njoro, Kenya	Field-level experiment to study impact of Vetiver and Napier grass strips
Angima et al. [*Angima et al.*, 2002, 2003]	Embu, Upper Tana, Kenya	Field-level experiment to study impact of Napier grass contour hedges
Okoba and Sterk [*Okoba and Sterk*, 2006a, 2006b, 2010]	Central Highlands	Combination of socio-economic surveys and field-experiments to estimate erosion baseline
Guto et al. [2011, 2012]	Central Kenya	Field-level assessment and cost-benefit analysis of minimum tillage and vegetative barriers
Green Water Credits program [*Kauffman et al.*, 2007, 2014; *Hunink et al.*, 2012b]	Upper Tana above Kiambere dam	Extensive field and modelling assessment quantifying current situation and potential of farm-level interventions
Physiographic Survey 2011 [*Z&A*, 2011]	Upper Tana above Kamburu dam	Intensive measurement campaign including bathymetric survey quantifying current situation and potential of farm-level interventions
Kenyatta University, team Prof. Gathenya [*Mwangi*, 2011]	Upper Tana above Sasumua dam	Modelling assessment of watershed feeding Sasumua dam

Obtaining reliable estimates from sediment yield and sediment loads measurements is highly difficult due to the extremely non-linear nature of the sediment discharge – stream discharge relationship. Brown and Schneider [1996] review estimates done in the Upper Tana by different authors and conclude that even based on the same datasets estimates may differ an order of magnitude due to different methods used. Dunne [1979] showed that for Kenyan basins the highest 10% of flows carries an average of 80% of the mean annual yield and the highest 1 % carries an average of 41 % of the yield. This implies that it is necessary to have accurate measurements of sediment loads during high flows. These high flow are often not captured during measurement campaigns [e.g. *Hunink et al.*, 2013]. A sampling scheme with a very high frequency is necessary, even with within-day intervals [e.g. *Walling et al.*, 1992].

Figure 1-7. Erosion on a steep slope in the Upper Tana

For the Tana Water Fund project, a dataset was made available which gives insight in the variable nature of the sediment loads in the basin. NCWSC provided a dataset on turbidity measured at the Mwagu intake where water is abstracted going to the Ngethu treatment plant (see Figure 1-5). Turbidity is an accurate proxy for sediment concentration, although the relationships can vary over time, depending on the sediment composition, and are usually different for each site. Figure 1-8 shows the minimum and maximum monthly turbidity measured at this measurement point (at a logarithmic scale). The figure also shows that variation within months can be very high.

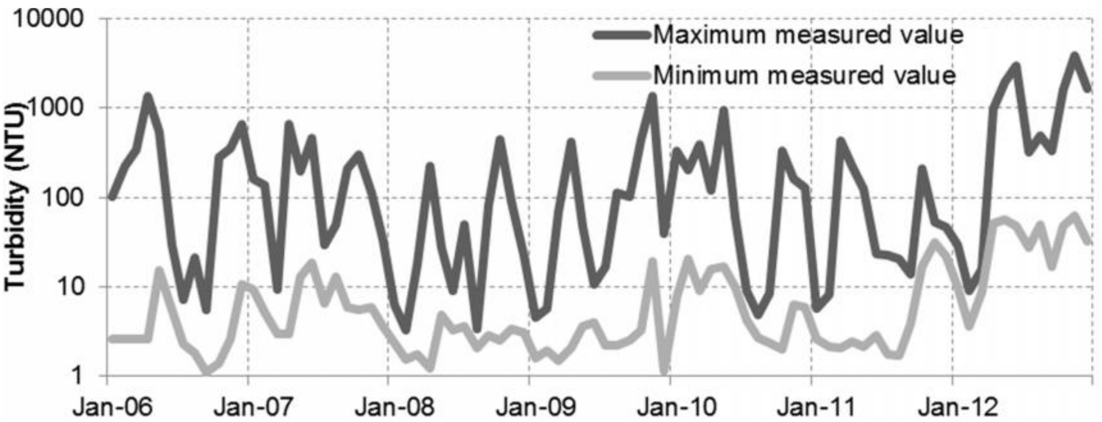

Figure 1-8. Minimum and maximum monthly sediment turbidity measured at the Ngethu intake

For long-term sediment yield assessments, bathymetric surveys can be carried out of reservoirs. These were conducted of four reservoirs in the Upper Tana basin (Masinga, Kamburu, Ndakaini and Sasumua) in 2011 for the Physiographic Survey study [*Z&A*, 2011]. These measurements were performed under favorable conditions with three out of four reservoirs near full supply level during the survey. Sediment budgets of the reservoirs were derived (see Figure 1-9) using estimates of sediment bulk density and the trap efficiency of the reservoirs. These estimated indicated that the Masinga reservoir has lost around 10% of its capacity since 1981, the Kamburu 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.

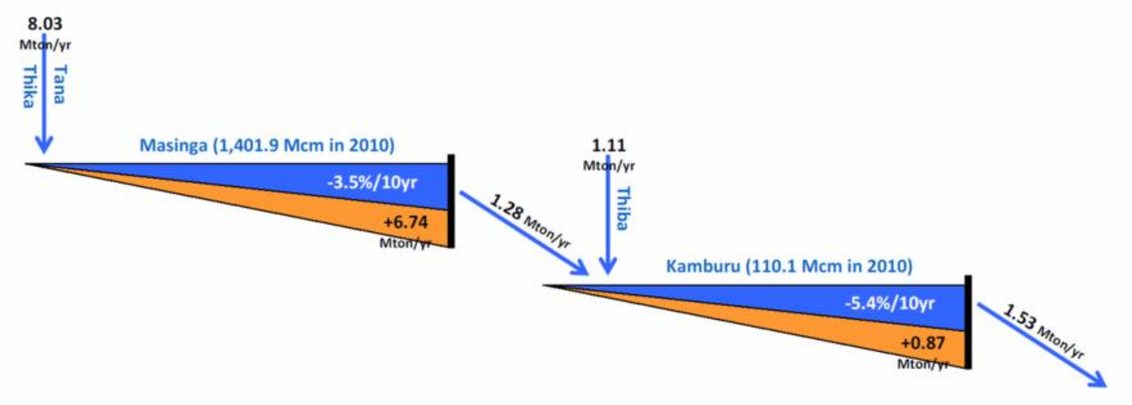

Figure 1-9. Sediment budget for the Masinga and the Kamburu reservoir [*Z&A*, 2011]

Also, the Physiographic Survey [*Z&A*, 2011] carried out a measurement campaign for sediment load, which helped to obtain a picture of the spatial variability of sediment loads throughout the Upper Tana catchment. However, the campaign was of short duration and only very few points fall within the priority watersheds. Due to lack of resources, after this campaign only very few additional measurements were carried out by WRMA (see Figure 1-10, please note logarithmic scale).

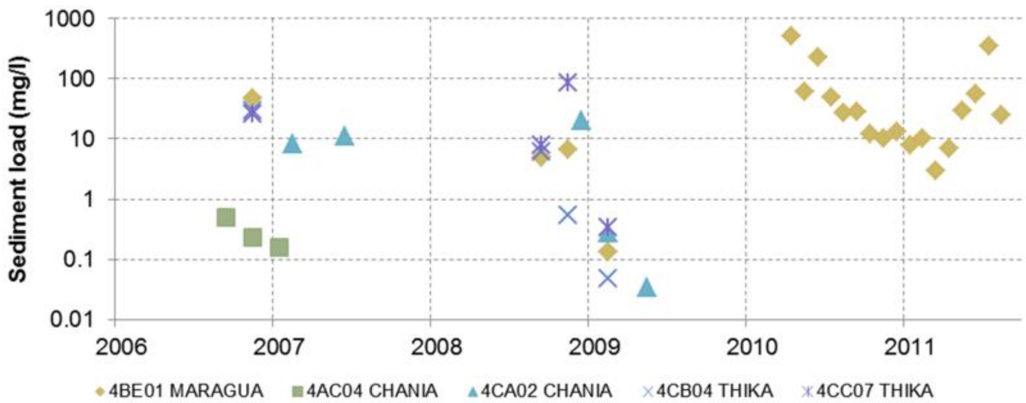

Figure 1-10. Sediment concentration measurements carried out by WRMA in period 2006-2011 within priority watersheds

1.5.3 Priority watersheds

Currently TNC is working with local partners to build capacity of upstream farmers in "water-smart" land-use techniques to increase crop yields and household income; maximizing the benefits they receive from nature because their watershed is healthy. The technical capacity of local conservation organizations is also strengthened. Water Fund partners are mobilizing communities to improve livelihoods, security and environmental conservation by planting trees to restore important habitat and ecosystem services in the Tana's upper watershed. By

Figure 1-11. Area where successfully grass strips were implemented in the Upper Tana

Three priority watersheds have been identified for the Business Case study (see Figure 1-12). These watersheds are: (1) Sagana, (2) Maragua , (3) Thika / Chania. The Thika/Chania catchment was selected because of its relevance for the Nairobi water supply, served by the Nairobi City Water and Sewerage Company (NCWSC). NCWSC is one of the principal stakeholders involved in the Water Fund, member of its Steering Committee and an active participant in the Business Case study providing crucial biophysical and economic data related to their activities.

The socio-economic survey data carried out in 2013 [*Leisher*, 2013] suggest that the Maragua sub-catchment has similar land and water-use issues than the Thika/Chania sub-catchment, and is of key interest for the Water Fund member KenGen. Besides, a new water diversion is planned from the Maragua catchment for NCWSC which makes this catchment also relevant for water supply.

The Sagana catchment was selected for potential stakeholders to be included in the Water Fund related with water supply (Nyeri town), and for its relatively high water yield from the catchments draining the Aberdares mountain range. Also, another key stakeholder in the Water Fund, the Green Belt Movement (GBM) is already active in the Gura sub-watershed being part of the Sagana watershed. This organization has several projects implemented to protect forest and riverine areas.

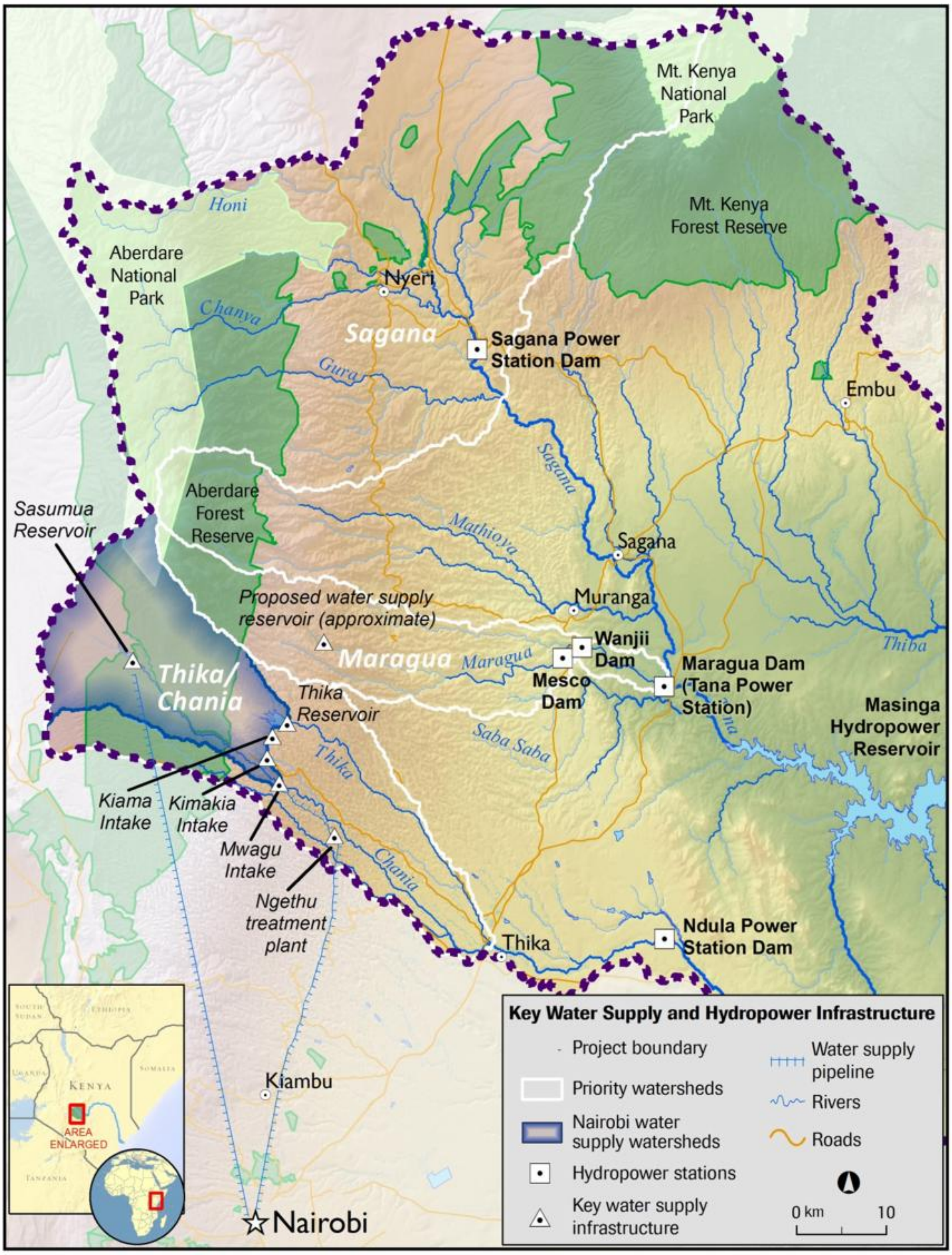

Figure 1-12. Location of the three priority watersheds in the Upper Tana basin

2 Modelling tool development

2.1 Overall approach to assessment

For the Business Case study of the Upper Tana River-Nairobi Water Fund, an innovative approach is used combining several state-of-the-art, yet widely used, tools: (i) RIOS to spatially target the investment portfolios, (ii) SWAT to assess the biophysical impacts and benefits of the investments, and (iii) different economic evaluation tools to estimate the economic benefits for upstream and downstream users.

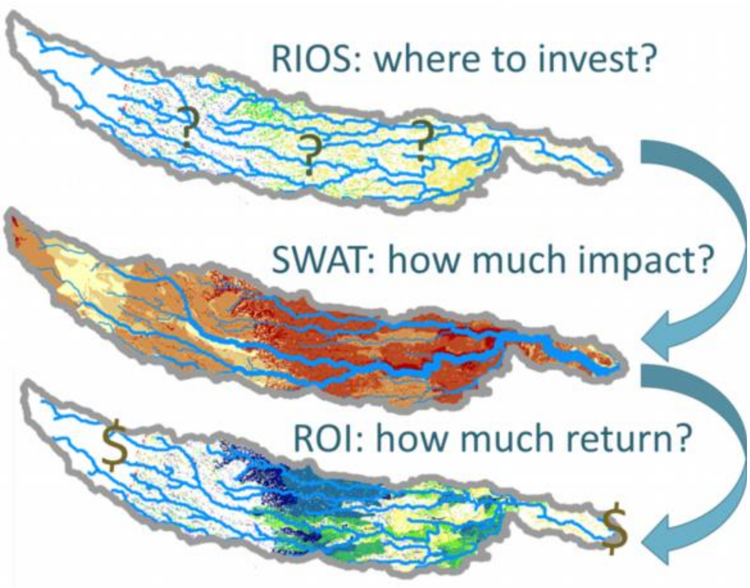

Figure 2-1. Overall modelling approach linking spatial prioritization tool RIOS, impact assessment model SWAT and the Return On Investment (ROI) analysis.

The RIOS tool is being developed by the Natural Capital Project (NatCap), and co-designed with users to improve returns from conservation investments based on a combination of biophysical, social and economic data. The tool has been tested in several emerging water funds across Latin America and has proven useful for managers and flexible enough to apply in different environmental, social, and legal contexts.

RIOS quantifies returns for some of the most desired water benefits including erosion control, water purification, and flood mitigation. The goal of RIOS is to provide a standardized approach to water fund design and investment prioritization in contexts throughout the world. For the Tana Water Fund, RIOS provides for a set of activities, the most appropriate locations considering both biophysical as well as stakeholder-related factors for each investment portfolio of the Water Fund.

To obtain a quantitative estimate of the benefits of the investment portfolios, a dynamic process-based hydrological model is required that accounts for temporal variability in inputs, parameters and outputs. Process-based models are very often used to explore the impacts of changes in land use and management in scenario studies. While application of many of these models is limited by their high data requirements, SWAT (Soil and Water Assessment Tool) is a process-based model that was successfully applied for catchments of different sizes, often in relatively data poor regions (e.g. Immerzeel and Droogers 2008, Schuol *et al.* 2008, Betrie *et al.* 2011). After calibration, the model can be applied at different spatial resolutions and levels of detail, and provides spatially distributed output of sources and sinks of sediment. This gives the model strong potential for use in scenario studies of changing land-use and management conditions (e.g. Tripathi *et al.* 2003, Mishra *et al.* 2007, Parajuli *et al.* 2008, Rostamian *et al.* 2008, Hunink *et al.*, 2013).

The RIOS portfolios are fed into the SWAT scenario and impact analysis. Crucial for this coupling is that the same input datasets (DEM, soil and land use) are used throughout the analysis. This way, the proposed activities can be linked directly to the SWAT calculation units. The SWAT outputs are used as inputs to the economic valuation for the upstream land users and for the downstream stakeholders (hydropower, water supply, etc).

2.2 Biophysical modelling specifications

2.2.1 Biophysical modelling approach

SWAT[1] was developed primarily by the United States Department of Agriculture (USDA) to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. The SWAT model has been extensively used, is in the public domain and can be considered as becoming the de-facto standard in ecosystem and watershed service assessments.

SWAT represents all the components of the hydrological cycle including: rainfall, snow, snow-cover and snow-melt, interception storage, surface runoff, up to 10 soil storages, infiltration, evaporation, evapotranspiration, lateral flow, percolation, pond and reservoir water balances, shallow and deep aquifers, channel routing. It also includes irrigation from rivers, shallow and deep groundwater stores, ponds/reservoirs and rivers, transmission losses and irrigation onto the soil surface. It includes sediment production based on a modified version of the Universal Loss Equation applied at a daily time step, and routing of sediments in river channels.

SWAT partitions the basin into a number of sub-basins. Within each sub-basin, each unique combination of soil, land use and slope is a calculation unit (referred to as Hydrological Response Units, HRUs). The simulation of the hydrology is separated into two domains. The first is the land phase of the hydrologic cycle, including all processes occurring before the water reaches the channel. This part of the model calculates for each calculation unit the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin. Then, the second conceptual domain of SWAT is the routing phase of the hydrologic cycle which simulates the transport of water and sediments through the stream network and providing output for each point of interest that is defined.

For the Water Fund business case study, the three priority watersheds were sub-divided in sub-basins and calculation units, based on the digital elevation model and the location of monitoring points and existing infrastructure. The high detail in input data, especially on land use (see more information in the respective section), results in a high number of calculation units and thus output on a highly spatial detail.

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[1] http://www.brc.tamus.edu/swat/index.html

Table 2-1 shows the number of sub-basins, calculation units and their size for each of the watersheds. As can be seen, the average size of the calculation units is 0.5 km2 for the three watersheds.

Table 2-1. Sub-basins, HRUs and their size for each of the watersheds

Watershed	Model	Total area (km2)	Number of sub-basins	Number of HRUs	Average area of HRU (km2)
Sagana	1	2029	460	2496	0.8
Maragua	2	464	99	1478	0.3
Thika/Chania	3	836	189	2124	0.4
Total		**3329**	**748**	**6098**	**0.5**

2.2.2 Erosion modelling

The Universal Soil Loss Equation (USLE) is the method most commonly used to estimate long-term erosion rates from field or farm sites that are subject to different management practices. Wischmeier and Smith (1965) developed the method based on data from many experimental plots in the USA, but the method has been applied and argued about, globally (e.g. Wischmeier 1976, Sonneveld and Nearing 2003).

The SWAT model estimates erosion and sediment yield with the Modified Universal Soil Loss Equation (MUSLE) [*Williams*, 1975]. While the USLE uses rainfall as an indicator of erosive energy, MUSLE uses the amount of runoff to simulate erosion and sediment yield. This modification is reported to increase the prediction accuracy of the model, the need for a delivery ratio is eliminated, and single storm estimates of sediment yields can be calculated [e.g. *Wang et al.*, 2008]. The MUSLE equation as used in SWAT is as follows:

$$Q_s = 11.8\,(Qr \bullet q_{peak} \bullet A_{HRU})^{0.56} \bullet K \bullet C \bullet P \bullet LS \bullet CFRG$$

where Q_s is the sediment yield (t/d); Q_r is the surface runoff volume (mm/ha); q_{peak} is the peak runoff rate (m^3/s); A_{HRU} is the area of the HRU (km^2); *K* is the USLE soil erodibility factor; *C* is the USLE cover and management factor; *P* is the USLE support practice factor; *LS* is the USLE topographic factor; and *CFRG* is the coarse fragment factor.

The USLE soil erodibility factor for each soil class can be calculated according to Williams [1995] which proposed the following equation and is broadly used, also recently in Kenya by Rahman et al., [2009] and Maeda et al. [2010] :

$$K = f_{\mathrm{csand}} \bullet f_{\mathrm{cl-si}} \bullet f_{\mathrm{orgc}} \bullet f_{\mathrm{hisand}}$$

where f_{csand} is a factor that gives low soil erodibility factors for soils with high coarse-sand contents and high values for soils with little sand, f_{cl-si} is a factor that gives low soil erodibility factors for soils with high clay to silt ratios, f_{orgc} is a factor that reduces soil erodibility for soils with high organic carbon content, and f_{hisand} is a factor that reduces soil erodibility for soils with extremely high sand contents. All these factors are calculated from the fractions of each texture class as in Williams which can be found in the soil dataset used. For the Upper Tana, the K factor ranges between 0.06 and 0.20. This is similar to what Mati et al. [2000] found for another basin in Central Kenya based on soil samples and what Dunne [1979] found for the Tana catchment.

The crop management factor of the USLE equation (C) is defined as the ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled, continuous fallow [*Wischmeier and Smith*, 1978]. This factor is recalculated by SWAT every day that runoff occurs and is a function of above-ground biomass, residue on the soil surface, and the minimum C factor for the plant [*Neitsch et al.*, 2005]. For the study catchments this value ranges between 0.003 (forested areas) and 0.4 (bare soil), and were based on literature values [*Mati et al.*, 2000; *Angima et al.*, 2003], and previous work in the catchment [*Hunink et al.*, 2012a, 2013].

For the support practice factor (P), reference values are used from literature [*Wischmeier and Smith*, 1978; *Renard et al.*, 1997; *Angima et al.*, 2003; *Arabi et al.*, 2008]. Currently, a part of the farmers has implemented soil conservation practices to some extent. From the socio-economic survey carried out in 2013 [*Leisher*, 2013], it was found that for the farmers that confirmed they had erosion problems on their land, a minimum of 15% and a maximum of 38% of their land is under soil conservation measures. Terracing (35%) followed by grass strips (30%) are the two primary soil conservation measures respondents take. Taking this baseline assessment into account, a baseline P factor value was used of 0.95, assuming already a minimum level of soil conservation practices that have been implemented.

The other factors (topographic factor LS and coarse fragment factor CFRG) of the erosion equation are evaluated as described by Wischmeier [1978] and are calculated by SWAT based on other input data (slope length, angle and % rock in soil).

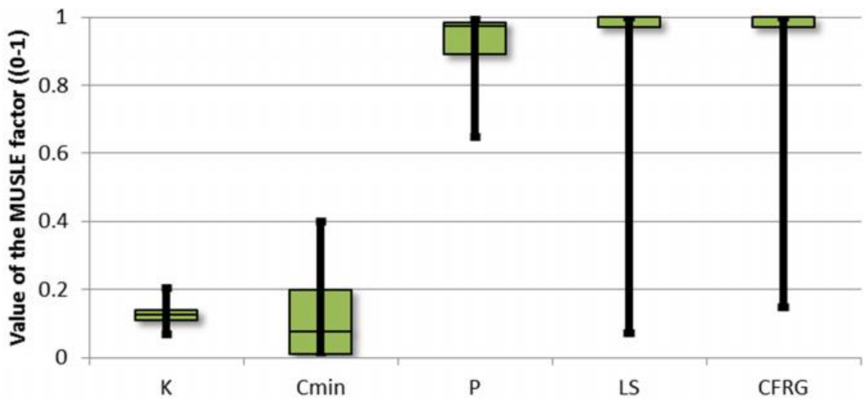

Figure 2-2. Boxplot showing the variability of the priority watersheds of the principal parameters of the of USLE equation

2.2.3 Sediment yield modelling

The sediment yields of each HRU are routed to the channel of the corresponding sub-basin. The transport of sediment in the channel is controlled by the simultaneous operation of two processes, deposition and degradation. SWAT uses Williams [1980] simplified version of Bagnold’s [1977] definition of stream power to develop a method for determining channel degradation as a function of channel slope and velocity. The maximum amount of sediment that can be transported from a channel segment is simulated as a function of the peak flow rate and is computed as follows:

$$S_{\max} = c_{\mathrm{sp}} (\frac{q_s}{A_{\mathrm{ch}}})^{\mathrm{sp}}$$

where S_{max} is the maximum concentration of sediment that can be transported or the channel carrying capacity (10^3 kg/m3); c_{sp} is an empirical coefficient which needs to be calibrated; q_s is the peak flow rate (m^3/s); A_{ch} is the cross-sectional area of flow in the channel; and *sp* is an exponent defined by the user.

If the concentration (S) in the reach segment is lower than S_{max}, degradation is the dominant process in the reach segment and the net amount of sediment reentrained is calculated

$$sed_{deg} = (S_{max} - S) \cdot V_{ch} \cdot K_{ch} \cdot C_{ch}$$

where sed_{deg} is the amount of sediment reentrained in the reach segment (tons), *Vch* is the volume of water in the reach segment (m3), K_{CH} is the channel erodibility factor (cm/hr/Pa), and C_{CH} is the channel cover factor.

The channel erodibility factor is conceptually similar to the soil erodibility factor used in the USLE equation. Channel erodibility (K_{CH}) is a function of properties of the bed or bank materials. Based on other SWAT-studies in tropical regions [*Betrie et al.*, 2011; *Wu and Chen*, 2012], the channel erodibility factor K_{CH} was set at 0.3.

The channel cover factor, C_{CH}, is defined as the ratio of degradation from a channel with a specified vegetative cover to the corresponding degradation from a channel with no vegetative cover. The vegetation affects degradation by reducing the stream velocity, and consequently its erosive power, near the bed surface. For this modeling study, the channel cover factor of 0.3 was used, as Moriasi et al. [2011] recommends for disrupted channels, e.g., due to constructions.

2.3 Modelling of the investment portfolios

2.3.1 Activities and investment levels

After consultation with the Tana Water Fund Steering Committee, local extension services, and other experts during the starting phase of the Business case study, a short-list of activities was made for the investment portfolios. These activities were input into the RIOS analysis, to prioritize them spatially in the watersheds based on multiple criteria, both biophysical as well as socio-economic ones.

The activities are the following (more details in main report [*TNC*, 2015]:

1. **Riparian management:** collection of activities to protect the riverine zone
2. **Agroforestry**: a conversion of crop lands to agroforestry
3. **Terracing**, *fanya juu:* similar to bench terraces, and known by its Swahili name, fanya-juu terraces are constructed by throwing soil up slope from a ditch to form a bund along a contour.
4. **Reforestation**: a conversion of croplands to forest
5. **Grass strips**: the planting of grass strips along the contours.
6. **Road mitigation**: different activities to reduce runoff and erosion from roads

Figure 2-3. Example of grass strips in the Upper Tana

For the Business Case analysis, a total of $10M budget was anticipated, to be spent over a period of 10 years. This total budget was distributed as follows among the three priority watersheds: Thika-Chania 45%; Sagana 30%; and Maragua 25%. This allocation was decided by the Steering Committee. It was also decided to distribute the total amount equally among the 6 activities. As example, Figure 2-4 shows the output of the RIOS tool for Maragua watershed for the 10 mUS$ investment portfolio.

To understand how the level of investment affects the return of investment, besides the 10 mUS$ investment, RIOS was run with two lower and one higher investment: a total investment of 2.5 mUS$, 5 mUS$ and 15 mUS$ over 10 years. For the Thika/Chania catchment, additional runs were done, in which the budget half of the budget (resp. 1.25 mUS$, 2.5 mUS$, 5 mUS$ and 7.5 mUS$) was used for prioritization only upstream of the Nairobi water supply abstraction points.

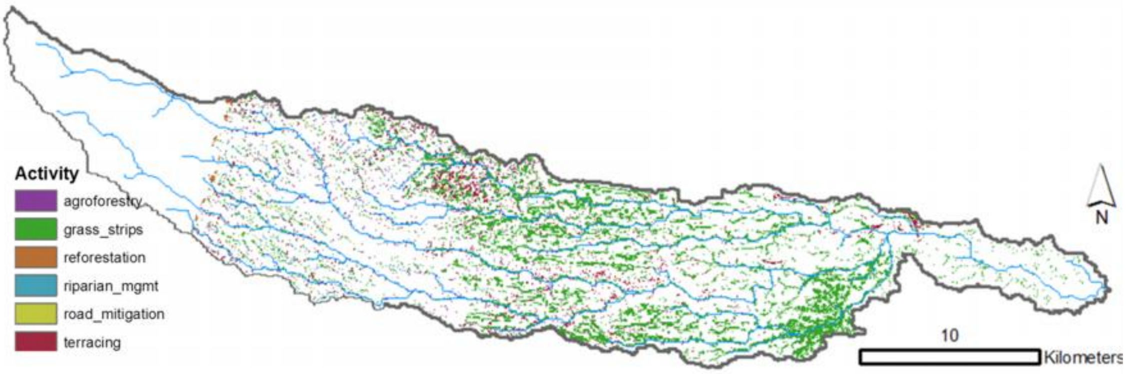

Figure 2-4. Activities proposed by RIOS for the 100% investment level in the Maragau watershed.

2.3.2 Implementing RIOS scenarios in SWAT

The RIOS tool provides maps for each investment portfolio that indicate which activity is most favorable given the set of criteria that were used as input (further details in the full report of the Business Case study). The RIOS tool takes into account the location of each field in relation to the river and it slope. Fields that are closer to the river have a higher potential to trap sediment from the upper slopes are assigned a higher score (more details in the RIOS documentation). In other words, the activities are targeted on those places where the highest response or impact can be expected.

If activities are implemented randomly without accounting for the different effectiveness that each field can have depending on its relative location, slope, soil and other factors, the scale of implementation must be linearly related with its impact (the random line in Figure 2-5). However, as explained before, RIOS takes into account many of the factors that influence the sediment yield from a combination of fields on slope. This means that the relationship between the number of fields and the total impact becomes non-linear: a small number of fields can already have a large impact. This non-linear dose-response relationship has been studied by various authors.

Tuppad *et al*. [2010b] used random and targeted methods to study the impact of BMPs (reduced tillage, edge of field vegetative filter strips, and contoured terraces) on pollutants. The BMPs were implemented on 10%, 26%, 52%, and 100% of the total targeted cropland and compared the pollutant reduction efficiency at the outlet of the watershed. They observed that the targeting method was more effective compared to the random method. White *et al*. [2009] used the SWAT model to quantify sediment and phosphorus loads at the watershed scale in Oklahoma. They observed that approximately 22% of the sediment and phosphorus load was originated from only 5% of the agricultural land. Similar dose-response relationship were found by [*Arabi et al.*, 2008] and Diebel *et al*. [2008].

The RIOS tool provides for each pixel ("field") in the land use map a recommended activity for each investment scenario. This means that different activities can be recommended for the same land use unit, or even the same field. The calculation units in SWAT are unique combinations of land use, soil and slope, which can be interpreted as a combination of similar fields within one sub-basin. This means that within one single calculation unit, different activities can be prioritized by RIOS. These activities are optimally located within each HRU on those places where the highest effectiveness can be expected according to the RIOS criteria. Therefore, when implementing the RIOS activities in the calculation units of SWAT, the previously described non-linear dose-response relationship was taken into account by calculating the implementation levels for each of the calculation units (HRU) and its corresponding effectiveness. The dose-response relationship used for this study as shown in Figure 2-5 was based on previous work in the catchment [*Kauffman et al.*, 2007; *Hunink et al.*, 2013] and [*Parajuli et al.*, 2008].

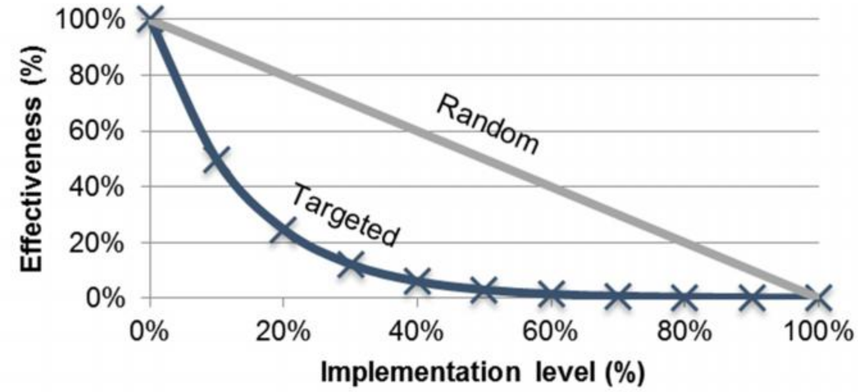

Figure 2-5. Dose-response relationship used for the mapping of RIOS activities to the SWAT model, compared to a random approach

2.3.3 Parameterization of scenarios

The RIOS portfolios of activities were represented in SWAT by adjusting the associated parameters (Table 2-2). The table shows the parameter changes, assuming 100% implementation. To calculate the actual parameter change, this change value is multiplied by the effectiveness that goes with %implemented_area. So the parameters are scaled using the the previously described dose-response relationship.

The following parameters were considered relevant for the activities to be implemented by the Water Fund:

- USLE_P – USLE equation support practice factor (-)
- CN2 – Initial SCS runoff curve number for soil moisture condition II (-)
- OV_N – Manning “n” value (-)
- HRU_SLP – Average slope steepness of HRU (m/m)
- ALPHA_BF – Baseflow alpha factor (days)
- GW_DELAY – Groundwater delay time (days)

Table 2-2. SWAT parameter (see description in text) changes for each activity

Activity	USLE P	CN 2	OV_N	HRUSLP*	ALPHABF*	GWDELAY*	Source
Riparian mgt	0.3	-5	0.15				Tuppad et al. [2010a]; Parajuli et al. [2008]
Agroforestry	0.6	-7	0.4		0.7	1.4	Wischmeier and Smith [1978]
Terracing	0.1	-7	0.2	0.7	0.8	1.3	Angima et al. [2003]; Renard et al [1997]; Tuppad et al. [2010a] ; Arabi et al [2008]; Wischmeier and Smith [1978]; Giri et al. [2014];
Reforestation	0.3	-7	0.4		0.5	1.8	Wischmeier and Smith [1978]
Grass strips	0.3	-5	0.15		0.7	1.4	Wischmeier and Smith [1978]; Arabi et al [2008]; [*Julien*, 2010]
Road mitigation	0.1	-10	0.15	0.9	0.7	1.4	[*Jungerius et al.*, 2002; *Nyssen et al.*, 2002; *Ziegler et al.*, 2004]
No soil conservation	0.95						Wischmeier and Smith [1978]; Leisher [2013]

3 Datasets used

3.1 Overview of datasets used

An overview of the dataset used for the SWAT impact assessment is provided here; details can be found in the following sections.

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 is 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.

TNC carried out a detailed update of the Africover land use maps, 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 was used for validation.

Sediment turbidity data were obtained from NCWSC for the Ngethu intake. Some data was available for 2010 on sediment loads in several point across the watersheds. Besides, long-term sediment loads were available based on the bathymetric survey carried out in 2010 of the Masinga dam and the NCWSC dams. The sampling data on sediment loads mainly of the year 2009 and only for a few points within the priority watersheds were not found to be representative enough to be used in this analysis.

3.2 Digital Elevation Model

Digital Elevation Model (DEM) data are used in SWAT to derive topographic attributes of the sub-basin, including area, slope, and field slope length. In SWAT, the watershed is divided into multiple sub-basins based on topographic features of the watershed. The topographic attributes are calculated at the sub-basin level and then assigned for the calculation units (HRUs) within the sub-basin. The slope is also separately calculated for each HRU.

In recent years many satellite-based methods for creating DEMs of the Earth's surface have become available, with the release of the space-borne SRTM (Shuttle Radar Topography Mission) and ASTER (Advanced Space borne Thermal Emission and Reflection Radiometer) elevation datasets. The DEM data from these two space missions cover most of the populated regions of the world and are publicly and freely available at a spatial resolution of 3arc s for SRTM and 1arc s for ASTER GDEM (ASTER Global DEM).

Generally, for hydrological modelling, preference is given by the scientific and modeling community to SRTM data. De Vente et al. [2009] found that SRTM90m provided more accurate estimates of slope gradient and upslope drainage area for soil erosion estimation than the ASTER30m in several Spanish catchments. Also other authors have found good results of using SRTM data in SWAT for estimation of soil erosion [*Lin et al.*, 2010; *Kinsey-Henderson and Wilkinson*, 2013].

Therefore, digital elevation data are used from the Shuttle Radar Data Topography Mission (SRTM) of the NASA's Space Shuttle Endeavour flight on 11-22 February 2000. SRTM data at 3 arc-second (90 meters) are available at global coverage between 60 degrees North and 56 degrees South latitude. The product consists of seamless raster data available in geographic coordinates (latitude/longitude) and is horizontally and vertically referenced to the EGM96 Geoid (NASA 1998). The SRTM-DEM data have been obtained using the USGS Seamless Data Distribution System (USGS 2004). Small voids present in the dataset within the area were filled by spatial interpolation. The dataset was resampled to the same resolution as the land use map (15m).

3.3 Soil data

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.

The dataset includes various soil properties necessary for SWAT modeling, as:

- Soil texture (sand, silt, clay and coarse fragments)
- Available Water Capacity
- Bulk density
- Organic carbon (for soil erodibility)
- Drainage class (for runoff curve number)

A key parameter lacking in the SOTER_UT database is saturated hydraulic conductivity. This property was estimated using the pedotransfer function put forward by Jabro (1992) and further detailed in Hunink et al. 2013.

3.4 Land use

TNC carried out a detailed update of the Africover land use maps, 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 (Figure 3-1).

Table 3-1 shows for each of the land use classes the percentage area of the total area of the watershed. As can be seen, coffee, tea and general agriculture are the main land use classes, in total covering more than half (52%) of the three priority watersheds. In the Sagana watershed however, coffee and tea are much less dominant then in the other two watersheds. Forest covers around 30% the Sagana and Thika/Chania watershed, but has a much smaller share in the Maragua watershed. Agroforestry is practiced on a reasonable percentage of the land (around 5%) in Thika/Chania and Maragua, while it is less common in the Sagana watershed.

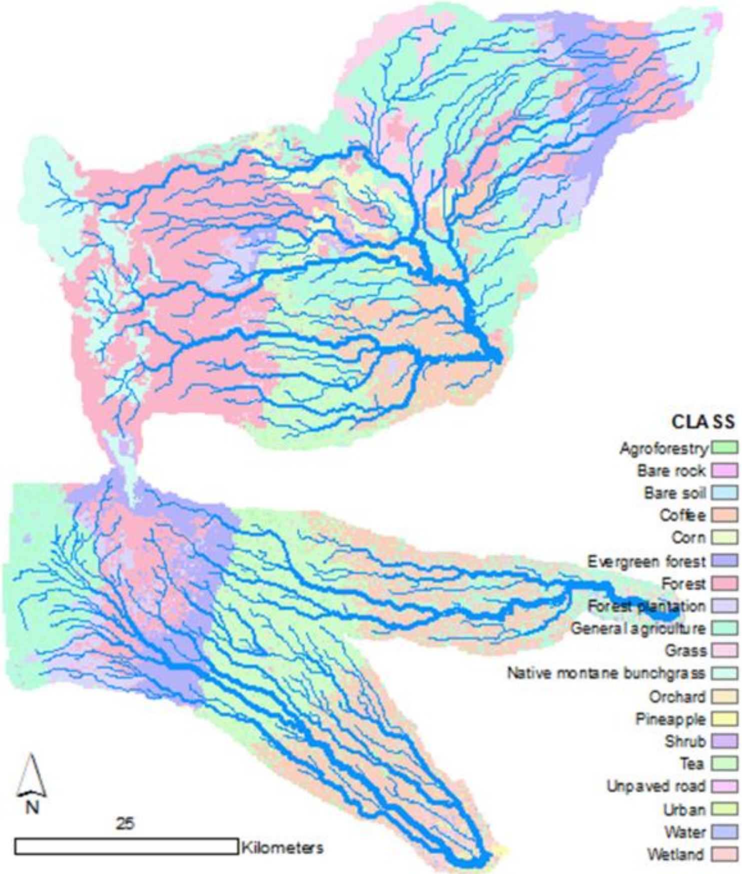

Figure 3-1. Land use map as used in the SWAT model for the three priority watersheds

Table 3-1. Percentage of each land use class for the three priority watersheds

Land use	Sagana	Maragua	Thika/Chania
Agroforestry	1%	4%	5%
Bare rock	0%	0%	0%
Bare soil	0%	1%	1%
Coffee	11%	29%	21%
Corn	4%	0%	0%
Evergreen forest	4%	12%	13%
Forest	31%	2%	14%
Forest plantation	5%	0%	7%
General agriculture	23%	20%	13%
Grass	4%	1%	1%
Native montane bunchgrass	8%	1%	0%
Orchard	0%	1%	0%
Pineapple	0%	0%	0%
Shrub	1%	1%	1%
Tea	6%	25%	20%
Unpaved road	1%	1%	1%
Urban	1%	1%	1%
Water	0%	0%	1%
Wetland	0%	1%	0%

The general agriculture class corresponds to a mixture of crops, mainly maize, as was confirmed by the socio-economic survey [*Leisher*, 2013], see also Table 3-2. In the upper parts of the watersheds, in March–May (long rain season) a mixture of maize, beans and vegetables are cultivated. Moving downwards one more drought-tolerant crops are cultivated as cowpea, pigeon pea and water melon. During the short rain season (October–December), traditionally more legumes and vegetables are cultivated, besides maize and other cereals. Along the river banks and valley bottoms small scale irrigation takes place by individual farmers or small groups, mainly for horticulture and floriculture. Some of these irrigation schemes have enabled year round cultivation although this is of relatively low importance in the catchments.

Figure 3-2. Tea plantation in the Thika/Chania watershed

Table 3-2. Crops cultivated by farmers according to the socio-economic survey carried out by TNC [*Leisher*, 2013]

Crops	Total
Maize	97%
Trees	91%
Napier Grass	90%
Pulses (beans, peas & lentils)	88%
Vegetables (pumpkins, sweet potatoes, greens, etc.)	84%
Bananas	83%
Coffee	40%
Tea	37%
Other	2%
Bamboo	1%

3.5 Weather input data

For this study, the following meteorological data sources are available and used (see Table 3-3) :

- Daily data from the Global Summary of the Day database (NOAA)

- Daily data obtained from WRMA
- Daily data obtained from NCWSC
- Monthly dataset elaborated within the Physiographic Survey Study, 2011.

Some of the stations are not within the watershed, but were used for gap filling and interpolation. The period covered by the data is 2000-2012.

Table 3-3. Meteorological stations used in the analysis.

ID	Name	Source	Daily / Monthly	Period	Lon	Lat
1	Embu	GSOD	Daily	2000-2012	37.450	-0.500
2	Nairobi	GSOD	Daily	2000-2012	36.917	-1.317
3	Nyeri	GSOD	Daily	2000-2012	36.950	-0.433
5	Kabaru Forest Station	WRMA	Daily	2000-2010	37.150	-0.283
6	Kiandogoro Gate	WRMA	Daily	2000-2010	36.750	-0.483
7	Muranga Water Supply	WRMA	Daily	2000-2012	37.150	-0.733
8	Wanjere Forest Station	WRMA	Daily	2000-2009	36.833	-0.683
9	South Kingagop Forest Stn	WRMA	Daily	2000-2007	36.683	-0.717
10	Thika Water Supply	WRMA	Daily	2000-2012	37.100	-1.033
11	Thika - Ndakaini Dam	NWC	Daily	2000-2012	36.850	-0.817
12	Sasumua Dam	NWC	Daily	2010-2012	36.667	-0.750
13	Karua Forest Guard Post	WRMA*	Monthly	2000-2009	37.183	-0.800
14	Kerugoya Castle Forest Stn	WRMA*	Monthly	2000-2009	37.317	-0.383
15	Kerugoya Water Development	WRMA*	Monthly	2000-2009	37.267	-0.500
16	Kiandogoro Hydromet	WRMA*	Monthly	2000-2009	36.833	-0.450
17	Kiriani Chief's Camp	WRMA*	Monthly	2000-2009	36.950	-0.600
18	Lower Kamweti Forest Guard	WRMA*	Monthly	2000-2009	37.350	-0.417
19	Muranga Muriranja's Hospital	WRMA*	Monthly	2000-2009	36.967	-0.750
21	Mwea Experimental Station	WRMA*	Monthly	2000-2009	37.350	-0.700
22	Mweiga Monte Carlo Ranch	WRMA*	Monthly	2000-2009	36.950	-0.333
23	Nyakio Estate	WRMA*	Monthly	2000-2009	37.017	-0.983
24	Nyeri Ministry of Works	WRMA*	Monthly	2000-2009	36.950	-0.417
25	Ragati Forest Station	WRMA*	Monthly	2000-2009	37.167	-0.383
26	Sagana Fish Culture Farm	WRMA*	Monthly	2000-2009	37.200	-0.667
27	Zaina Forest Station	WRMA*	Monthly	2000-2009	36.817	-0.417

* From Physiographic Survey Study, 2011

To obtain a quality checked database as input for SWAT modeling, the following steps have been followed and will be further described after:

- Quality check of all station data
- Gap filling of daily stations based on correlations with the other stations
- Temporal downscaling of monthly dataset to daily

Annual sums and monthly sums were checked for consistency. This was done by checking whether the anomalously high or low vales in the time series, and comparing annual sums with the closest stations. Some stations contained data indicating zero rainfall, but annual sums indicated that this should in fact be a non-observed (no data) value. These values have been deleted from the dataset.

The resulting daily data contained several data gaps that need to be filled. This has been done based on the correlation of each station with the other stations. To create the reference series we considered all the stations and a virtual additional station calculated from the mean daily precipitation of all the stations, as follows:

$$P_y(t) = \sum_{i=1}^{n} w_x(a * P_x(t) + b)$$

in which P_y(t) is the in-filled precipitation for station y on day *t*, w_x is the weighting factor for station *x*, *a* and *b* are coefficients of the linear regression with the each of the other stations and P_x is the precipitation for station *x*. The weighting factors are derived from the coefficient of determination between each of the stations.

The stations for which monthly data was available have been temporally downscaled using the data of the daily station closest to each one, by:

$$P(t) = P_m * \frac{P_x(t)}{P_{x,m}}$$

in which in which *P*(t) is the precipitation for station on day t, P_m is the accumulated precipitation in month m, $P_{x(t)}$ is the daily precipitation of the closest station, and $P_{x,m}$ is the monthly accumulated station of this station.

The final dataset covers the entire study period (2000-2012) for all stations listed in Table 3-3. Figure 1-2 shows the map of all stations, in which the mean annual precipitation (based on 2000-2012) was spatially interpolated (*spline*). The mean annual precipitation in the priority watersheds ranges between 700 (lower areas) and 1700 mm (Aberdares mountain range).

3.6 Streamflow

Data on discharge was made available for this study by WRMA for different points throughout the watersheds. Data was obtained covering the period 2000 - 2012. Some stations have only data for a part of this period, and some contain significant data gaps. Table 3-4 provides an overview of the gauging stations of which data is available on streamflow. All the stations were subject to a quality review, to check their consistency and usefulness for calibration. The stations that did not pass the quality check are greyed out in the table.

For the Sagana watershed, the gauging station at the outlet of the Gura tributary was chosen, as it proved to be of relatively good quality. Also this watershed is less altered by human interference upstream which makes it more suitable for calibration then others in the Sagana watershed. For the Maragua watershed, only one station was available, downstream of the watershed. For the Thika/Chania watershed the inflow of the Thika dam was chosen for calibration. Data was received from NCWSC and showed to be relatively complete and consistent.

Table 3-4. Stations where streamflow data is available in priority watersheds and observations. Highlighted stations are selected for comparison with simulations.

WRMA station code	Priority water-shed	Q_start	Q_end	Comments
4AC03	1	2000	2009	Many data gaps within study period
4AC04	1	2000	2012	Re-installed in 2000, but first 4 years not consistent with rest of the period.
4AC05	1	2000	2012	Many data gaps within study period
4AD01	1	2000	2009	Downstream of tributary Gura of Sagana watershed.
4BE01	2	2000	2012	Only station in Marugua watershed. Relatively complete, and downstream.
4CA04	3	2000	2012	Many data gaps within study period
4CB04	3	2000	2009	Highly altered regime due due to close irrigation reservoirs, not ideal for calibration
4CB07	3	2000	2012	Many data gaps and unclear coordinates.
4CB08	3	2000	2012	Coordinates not clear, but no data within period
Thika inflow	3	2000	2012	Inflow data of Ndakaini (Thika) dam, provided by NCWSC. Relatively complete

4 Model performance

4.1 Streamflow

The runoff produced by each HRU, is routed through the channel network, for which SWAT uses the Manning´s equation and the Muskingum river routing method. Thus, simulated streamflow in each point of the watershed can be compared with measured streamflow at the different points that were selected. For scenario analysis using watershed models, it is important that the variability in streamflow is well captured and compares well with the observed variability [*Jothityangkoon et al.*, 2013; e.g. *Condon and Maxwell*, 2014]. Figure 4-3 shows for each of the three models, the monthly observed and simulated streamflow.

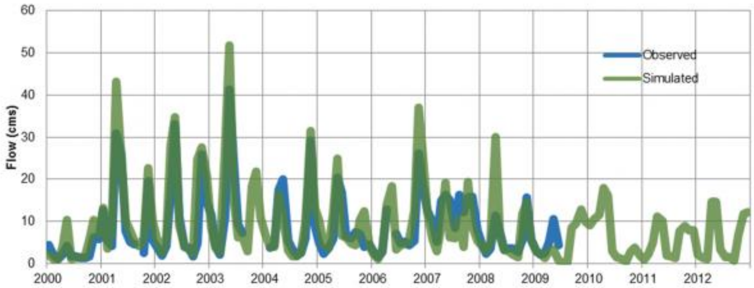

Figure 4-1. Observed versus simulated streamflow for the Sagana (Gura tributary, point 4AD01)

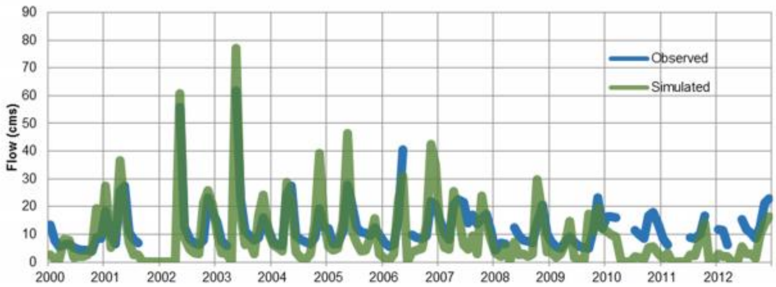

Figure 4-2. Observed versus simulated streamflow for the Maragua watershed (point 4BE01)

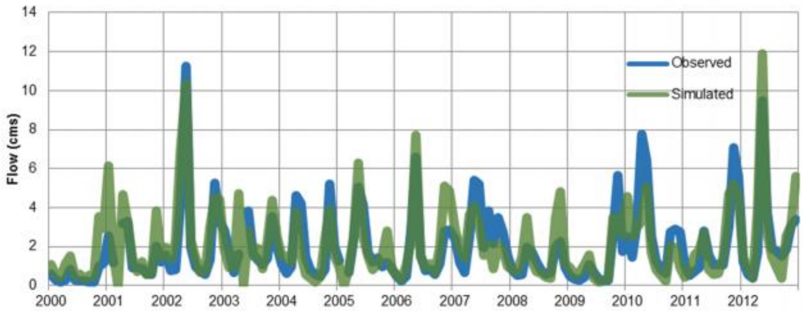

Figure 4-3. Observed versus simulated streamflow for the Thika/Chania watershed (inflow Thika dam)

Common performance indicators for the evaluation of watershed models are the Pearson Product-Moment Correlation Coefficient (PMCC) [*Bennett et al.*, 2013], which calculates the correlation between two series of sampled data and lies between -1 and 1. Other common indicators [*Moriasi et al.*, 2007] are the Root Mean Square Error, here normalized with the range over observed values, and the Percent Bias. A fourth performance indicator used is the Nash and Sutcliffe (1970) efficiency (NSE) criterion, the most commonly used for evaluating hydrological models. The NSE ranges between −∞ and 1.0, with NSE = 1.0 being the optimal value.

Table 4-1 shows these four performance indicators for the three priority watershed models. As can be seen from this table and from Figure 4-3, the model performance satisfactory for all of the models. The Pearson coefficient is relatively close to 1 for each model, the Normalized RMSE is around 10%, the percent bias ranges between -17% and 9%, and the NSE criterion ranges between 0.3 and 0.6.

Table 4-1. Performance indicators of the three watershed models

Performance indicator	1. Sagana	2. Maragua	3. Thika/Chania
Pearson coefficient (0-1)	0.86	0.84	0.82
Normalized RMSE (%)	13%	12%	10%
Percent Bias (%)	1%	-15%	9%
Nash- Sutcliffe coefficient (0-1)	0.6	0.3	0.6

Based on this validation the models were considered to be suitable to be used for scenario analysis. Moreover, it should be taken into consideration that the uncertainty related to the predicted relative changes of scenario outcomes are smaller than the prediction uncertainty of absolute model outcomes (Arabi *et al.* 2007, Droogers *et al.* 2008).

4.2 Sediments

NCWSC provided data on turbidity at the Mwagu weir where water is abstracted for the Ngethu treatment plant coming from the Chania and Thika watersheds. SWAT simulates sediment concentrations which are normally linearly related with turbidity although this relationships tends to be location and even time-dependent.

Figure 4-5 shows a scatterplot of daily measured turbidity values against daily simulated sediment concentrations at the Ngethu intake. For both timeseries the 20-day moving average was used for this plot. The figure shows a clear linear relationship between both variables. This linear relationship was used to convert sediment concentration values to turbidity values for this point.

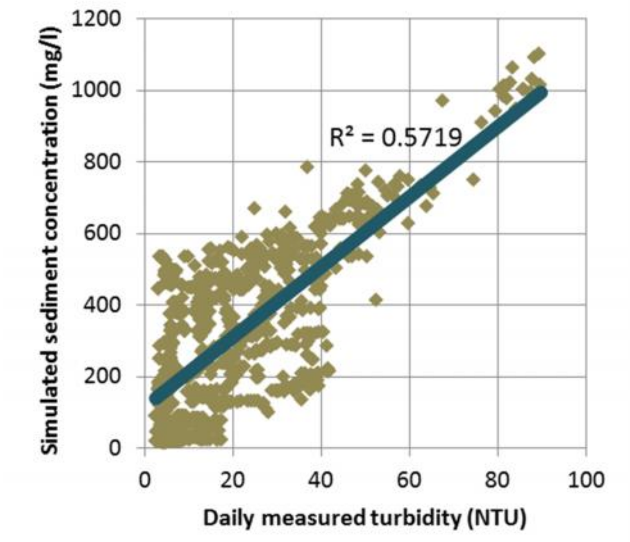

Figure 4-4. Daily turbidity values versus daily simulated sediment concentration for the Ngethu intake

Another way to verify whether the model represents well the seasonality in sediment concentrations is by looking at the monthly pattern. When comparing mean monthly turbidity values with the mean monthly sediment loads at the Mwagu weir, a similar pattern is found (Figure 4-5), indicating that the model represents reasonably well the sediment dynamics in the catchments.

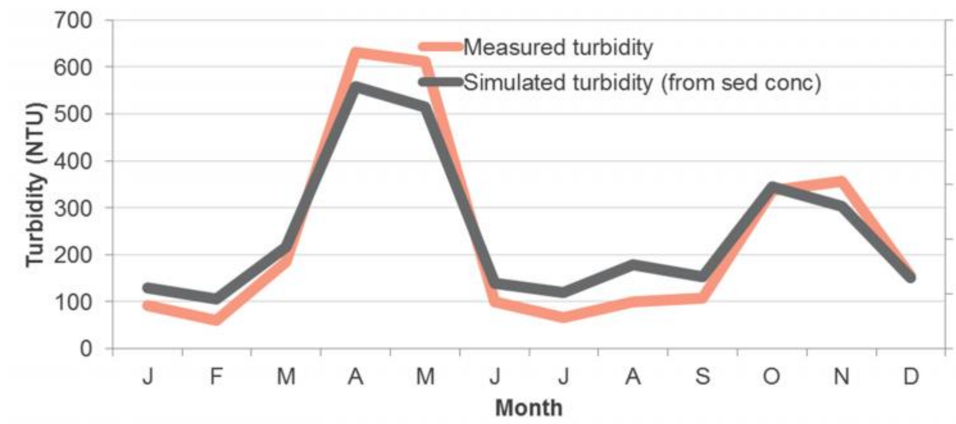

Figure 4-5. Monthly measured turbidity (max) versus simulated sediment concentration for the Ngethu intake

For sediment loads, the only reliable data source available is coming from the Physiographic Survey study (2011). This survey estimated an average sediment inflow into Masinga of 8.0 Mtons/yr. Figure 4-6 shows the total sediment loads coming from the three priority watersheds. As can be seen they are highly variable depending on the rainfall regime and hydrologic response each year. The average annual total load is 5.0 Mtons/yr, meaning that the priority watersheds provide around 63% of the total sediment inflow in Masinga. Of this total, simulations showed that Maragua provides on average 25%, Thika/Chania 36% and Sagana 39%.

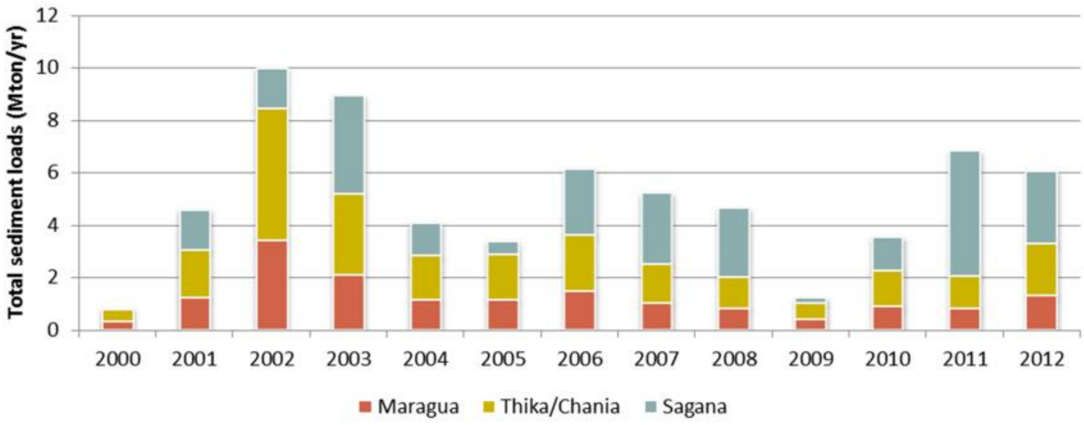

Figure 4-6. Total sediment loads from the three priority watersheds

4.3 Crop growth

SWAT includes a crop growth module. The main output variable that drives biomass production and crop transpiration is the so-called Leaf Area Index (LAI). LAI is a dimensionless quantity that characterizes plant canopies. It is defined as the one-sided green leaf area per unit ground surface area (LAI = leaf area / ground area, m2 / m2). LAI is often used to predict photosynthetic primary production, evapotranspiration and as a reference tool for crop growth.

Over large areas LAI is often estimated from remotely sensed images. The MODIS satellites provide data from which LAI is derived and provided free of charge. For this study, the LAI product from MODIS data was downloaded and the LAI statistics were extracted for each of the crop classes.

Table 4-2. Average satellite derived LAI for each crop versus simulated in the three watersheds

Land use	Observed	Simulated		
Crop	Entire area	Maragua	Thika/Chania	Sagana
Coffee	2.0	2.3	2.2	2.2
Evergreen forest	3.7	4.0	4.0	3.3
Forest	3.7	3.5	3.6	2.9
Forest plantation	3.2	3.6	3.6	2.9
General agriculture	1.6	0.8	0.8	0.8
Grass	1.2	1.2	1.2	1.2
Montane bunchgrass	1.1	1.0	1.0	1.7
Orchard	1.5	2.2		
Pineapple	1.0		1.7	
Shrub	2.0	1.1	1.4	1.4
Tea	3.9	3.5	3.5	3.5
Wetland	1.2	0.9		

Table 4-2 and Figure 4-7 compare for each crop class in the Upper Tana priority watersheds the satellite-derived LAI value (annual average) with the simulated value by SWAT. The correspondence is reasonably well for average values. Obviously LAI is highly variable in space and time, making the comparison much more complex taking into account all dimensions. But this first-order comparison provides some confidence that the model provides realistic estimates of crop growth. At the same time it has to be noted that the uncertainties in both the satellite-derived as well as the simulated LAI are relatively high and a full validation of these values requires a deeper study.

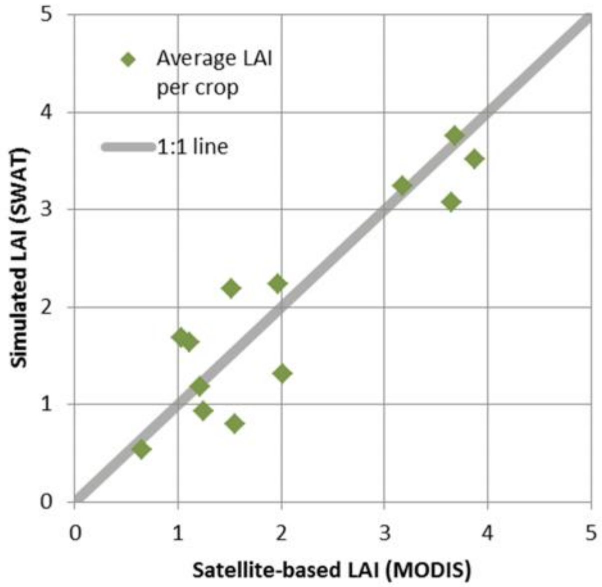

Figure 4-7. Scatterplot showing average values for each crop for satellite-based LAI versus simulated LAI.

5 Impact of interventions

This chapter presents the impact of the investment portfolios on erosion and sediment loads for the three priority watersheds. The basis for these analyses was the simulation of the RIOS investment portfolios (where to do what) into quantifiable impacts (erosion, turbidity, flows).

5.1 Sagana watershed

The RIOS tool prioritized the 6 activities across the Sagana watershed for all the investment levels. Figure 5-6 shows the map of proposed interventions for the 10mUS$ investment scenario. These spatial distributions were used as input for the SWAT model analysis to calculate impacts on erosion, sediment concentrations, sediment loads and flows.

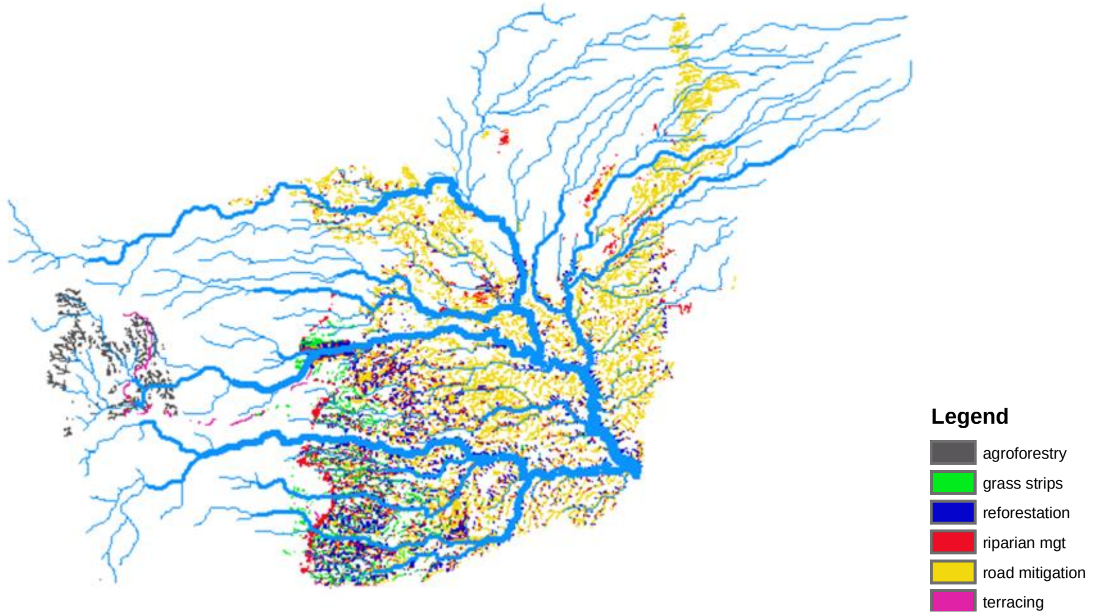

Figure 5-1. Activities proposed by RIOS for the 100% investment level in the Sagana watershed.

SWAT simulates for each spatial unit the absolute and relative changes in the hydrological response, as runoff, erosion, sediment yield and others. These relative changes include the average change of the spatial calculation unit and depend on the area and type of activities that take place. Figure 5-7 shows the average annual erosion (ton/ha) for the current situation and Figure 5-8 for the 10 mUS$ investment level.

The Figure shows that the spatial variability is large, influenced by the biophysical conditions as slope, soil type and land use. The difference between both scenarios shows where the impact is highest of the activities. Figure 5-9 shows the reduction in erosion for this watershed under the 10 mUS$ scenario. Please note that these maps show the erosion levels per calculation unit (HRU) of the SWAT model and give insight in the spatial distribution of impacts on the watershed level. A calculation unit aggregates several fields ("pixels") with the same land cover but often only a portion of the area activities take place. This means that on the field level, the reductions are even higher (see also Chapter 6).

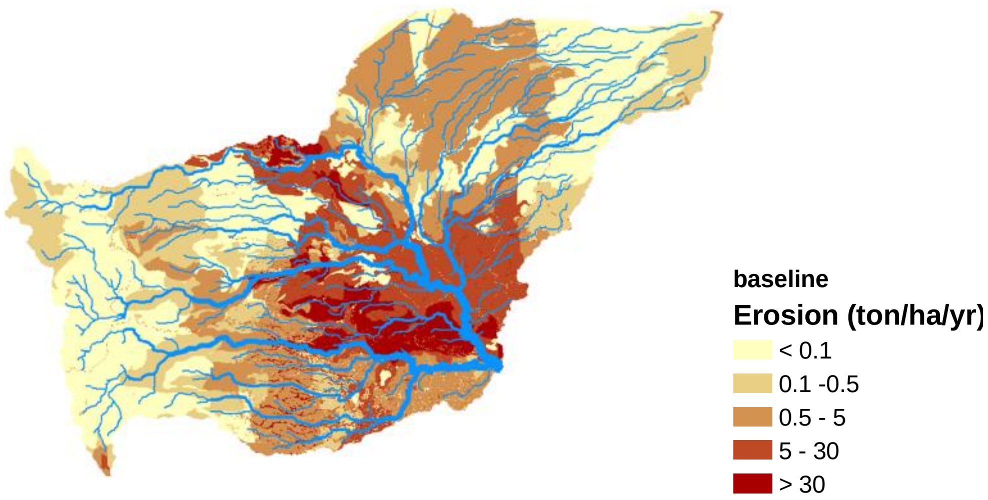

Figure 5-2. Average erosion rates for the baseline scenario (ton/ha/yr) for the Sagana watershed

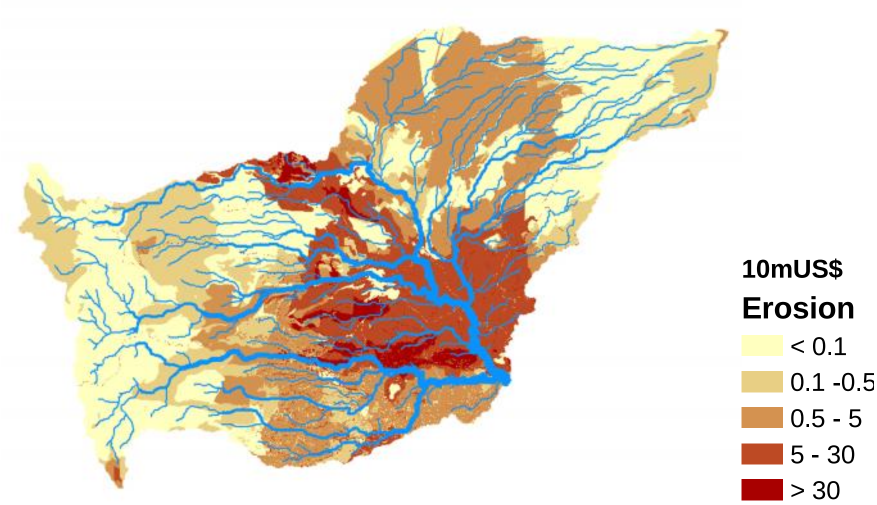

Figure 5-3. Average erosion rates for the 10 mUSD investment scenario (ton/ha/yr) for the Sagana watershed

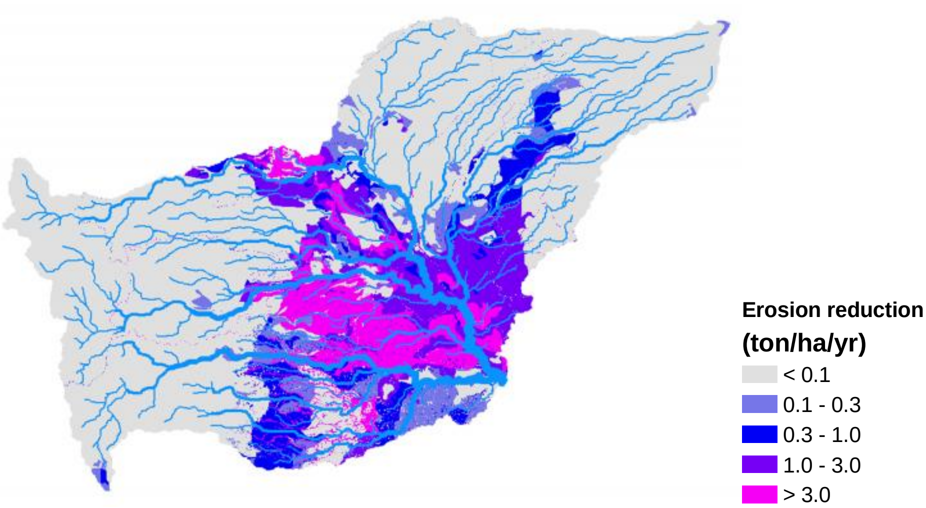

Figure 5-4. Erosion reduction for the 10 mUSD investment scenario (ton/ha/yr) for the Sagana watershed

The principal land use classes where activities are targeted by RIOS are shown in Table 5-2, which shows the total reduction in sediment yield coming from these land use classes in tons. Most of the reduction originates from general agriculture. Also sediment yield from coffee fields will reduce significantly. A major focus of the RIOS targeting was put on unpaved roads, which results also in fair share of reductions in sediment yield. Figure 5-5 shows the relative reductions for the same land use classes. In relative terms the reduction is highest for the degraded lands ("bare soil" in the landuse map) but has a very minor share in the total reduction.

Table 5-1. Average reduction (tons) in erosion coming from the principal land use classes where activities are planned under the different investment levels

Scenario	Degraded lands	Coffee	General agriculture	Tea	Unpaved road	Total
2.5mUS$	-2,302	-26,321	-42,916	-1,772	-5,413	-78,724
5mUS$	-2,993	-33,837	-74,703	-2,203	-7,626	-121,362
10mUS$	-3,062	-54,635	-131,425	-3,246	-19,821	-212,188
15mUS$	-3,070	-93,707	-193,473	-3,525	-26,120	-319,895

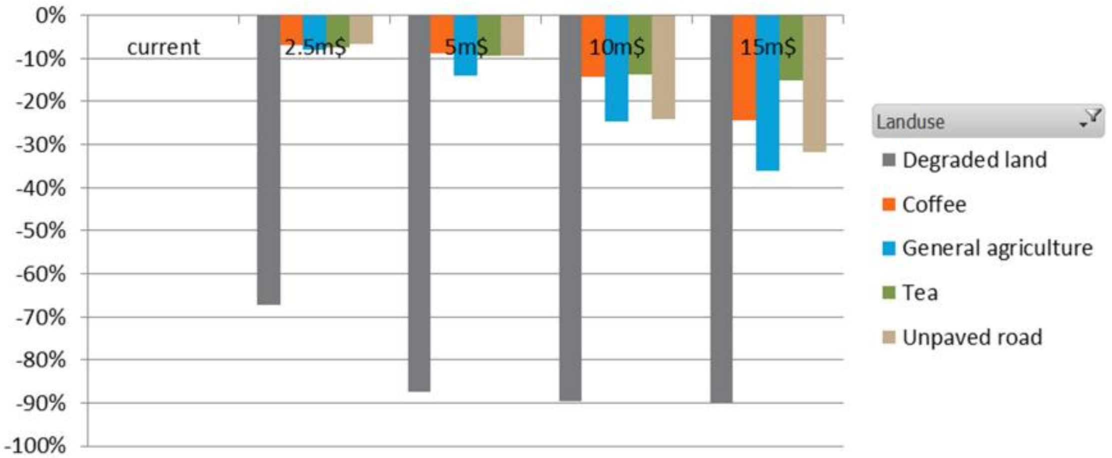

Figure 5-5. Average relative reduction (%) in sediment yield for the various investment scenario compared to the current situation

5.2 Maragua watershed

Figure 5-6 shows the map of proposed interventions for the 10mUS$ investment scenario that were prioritized by the RIOS tool across the Maragua watershed. This spatial distribution and the ones of the other investment levels were used as input for the SWAT model analysis to calculate impacts on the different biophysical outputs.

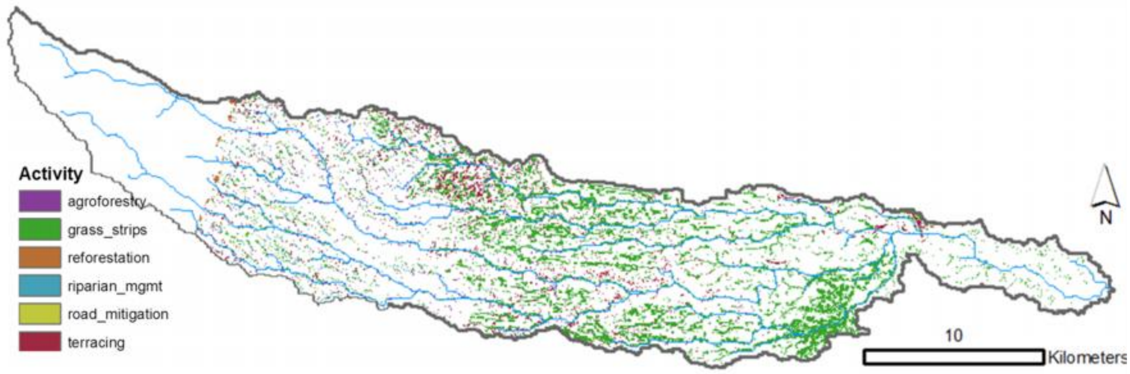

Figure 5-6. Activities proposed by RIOS for the 100% investment level in the Maragau watershed.

SWAT predicts the erosion and sediment yields for all the calculation units in the watershed and for the different investment scenarios. Figure 5-7 shows the average annual erosion (ton/ha) for the current situation and Figure 5-8 for the 10 mUS$ investment level. The difference between both scenarios shows where the changes in sediment yield are predicted to happen and the level of change. Figure 5-9 shows the reduction in erosion for this watershed under the 10 mUS$ scenario.

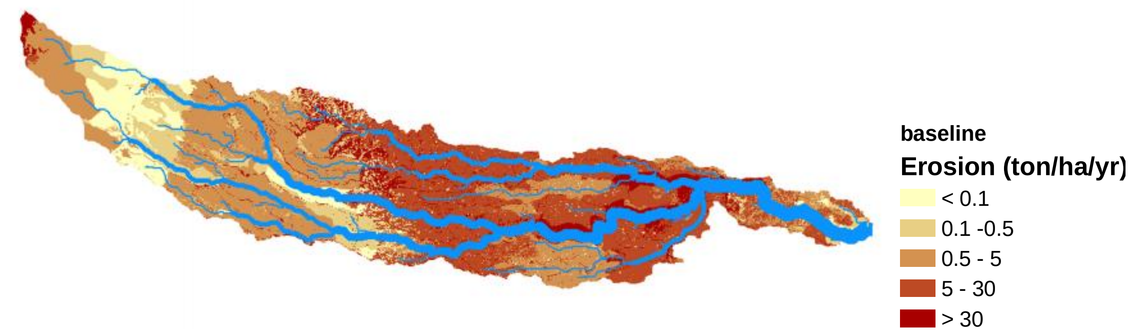

Figure 5-7. Average erosion rates for the baseline scenario (ton/ha/yr) for the Maragua watershed

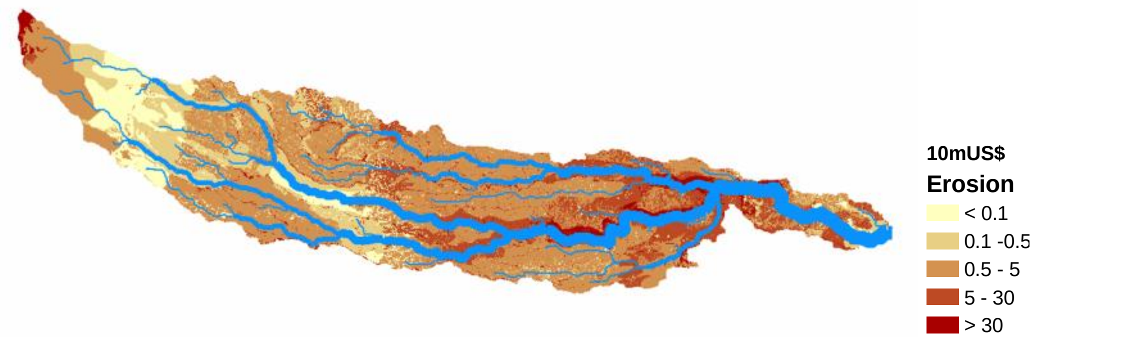

Figure 5-8. Average erosion rates for the 10 mUSD investment scenario (ton/ha/yr) for the Maragua watershed

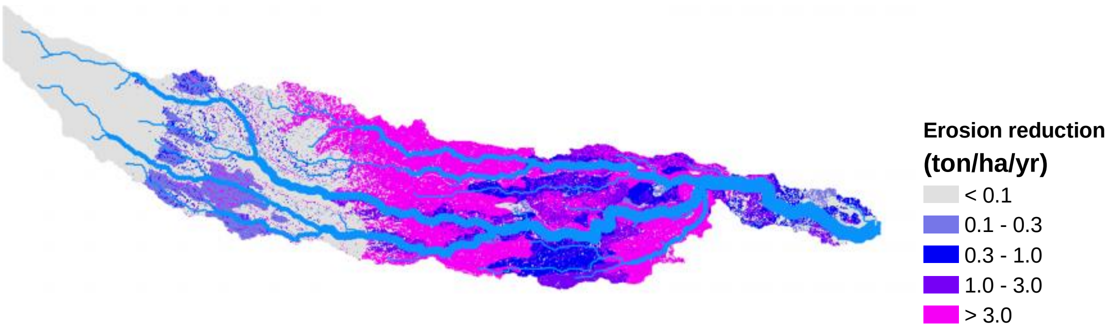

Figure 5-9. Erosion reduction for the 10 mUSD investment scenario (ton/ha/yr) for the Maragua watershed

Table 5-2 shows the total reduction in sediment yield coming from the principally prioritized land use classes. For this watershed a relatively high investment is proposed in the degraded lands. Most of the reduction in this watershed originates from these areas. Also sediment yield from general agriculture and coffee fields are reduced significantly. Another focus was put on unpaved roads resulting in significant reductions in sediment yield. Figure 5-5 confirms the relative impact on sediment yield from degraded lands and unpaved roads. Fewer activities take place in tea areas and at the same time these lands are not a very significant contributor to total erosion, so the reductions are relatively small.

Table 5-2. Average reduction (tons/year) in erosion coming from the principal land use classes where activities are planned under the different investment levels

Scenario	Degraded land	Coffee	General agriculture	Tea	Unpaved road	Total
2.5mUS$	-115,365	-11,240	-7,719	-289	-75,247	-209,859
5mUS$	-136,085	-44,870	-22,723	-503	-90,654	-294,835
10mUS$	-142,395	-100,370	-54,481	-863	-100,457	-398,566
15mUS$	-142,666	-129,098	-89,201	-1,345	-104,683	-466,993

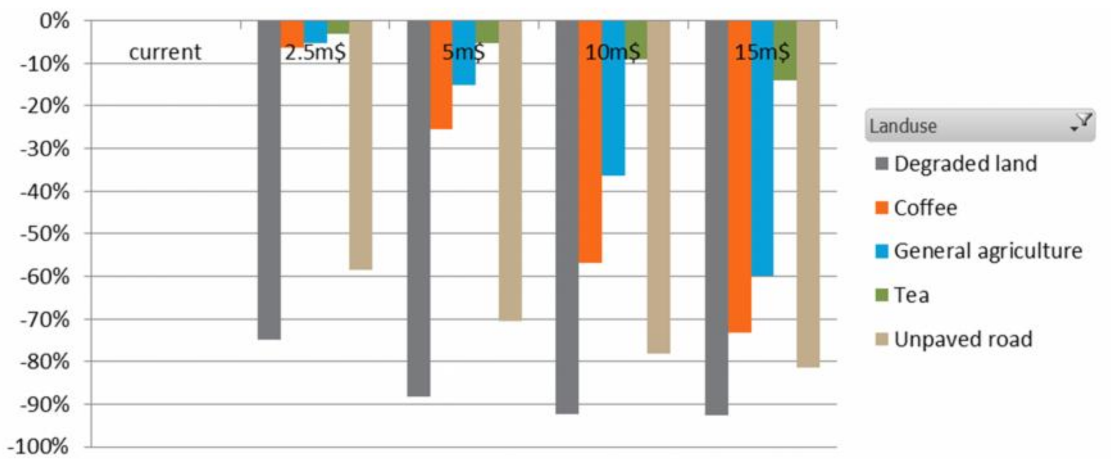

Figure 5-10. Average relative reduction (%) in erosion in the Maragua watershed for the different investment scenarios compared to the current situation

5.3 Thika/Chania watershed

Because of the importance of the Thika/Chania watershed for Nairobi water supply, several additional scenarios and investment levels were analyzed. The RIOS tool also considered investment scenarios in which the budget was allocated only upstream of the abstraction points for Nairobi water supply. So for this watershed there are twice as many scenarios as for the other two watersheds. The investment levels analyzed are: 2.5 mUS$, 5 mUS$, 10 mUS$ and 15 mUS$ with prioritization over the entire watershed, and 1.25 mUS$, 2.5 mUS$, 5 mUS$ and 7.5 mUS$ for prioritization for only the part upstream of Nairobi water supply. The set of investment levels all assume that half the budget was allocated to protect the Nairobi water supply abstraction points. So for example, the “5M” scenario “contains” the 2.5M scenario that is focused on the Nairobi water supply.

Figure 5-6 shows the map of proposed interventions for the 10mUS$ investment scenario in the Thika/Chania watershed. These spatial distributions were used as input for the SWAT model analysis to calculate impacts on erosion, sediment concentrations, sediment loads and flows.

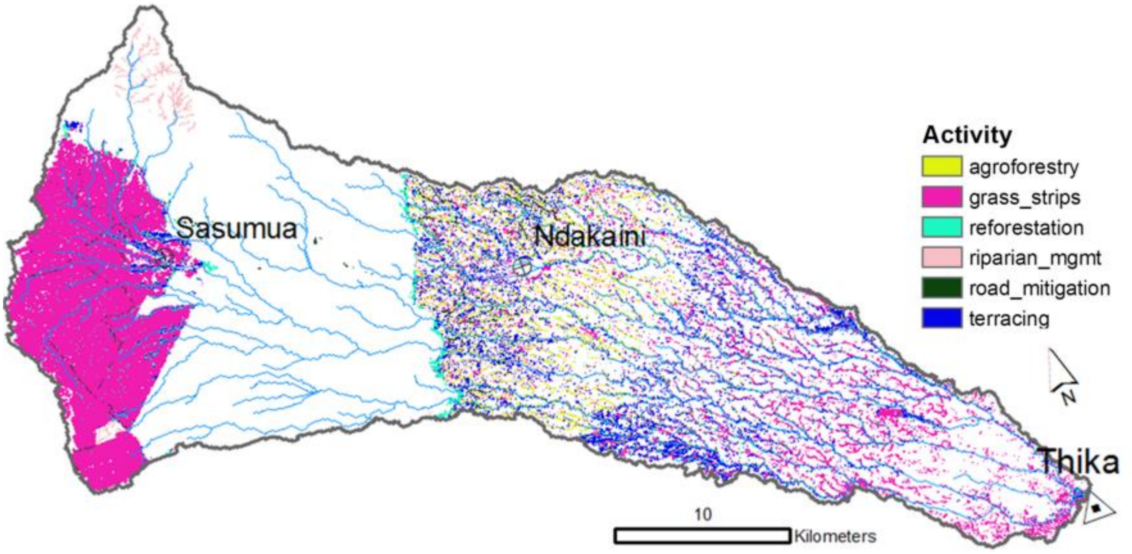

Figure 5-11. Activities proposed by RIOS for the 100% investment level in the Thika/Chania watershed.

The SWAT output provides the spatial distributions of water and sediment flow for each of the investment levels. Figure 5-12 shows the average annual erosion (ton/ha) for the current situation and Figure 5-13 for the 10 mUS$ investment level. The spatial variability is large depending principally on slope, soil type and land use, but also precipitation regime is an important factor.

The difference between both the scenarios and the current situation shows where the impact of the activities is highest. These impacts are based on the average change for each spatial calculation unit and depend on the type and number of activities taking place. Figure 5-14 shows the reduction in erosion for this watershed under the 10 mUS$ scenario.

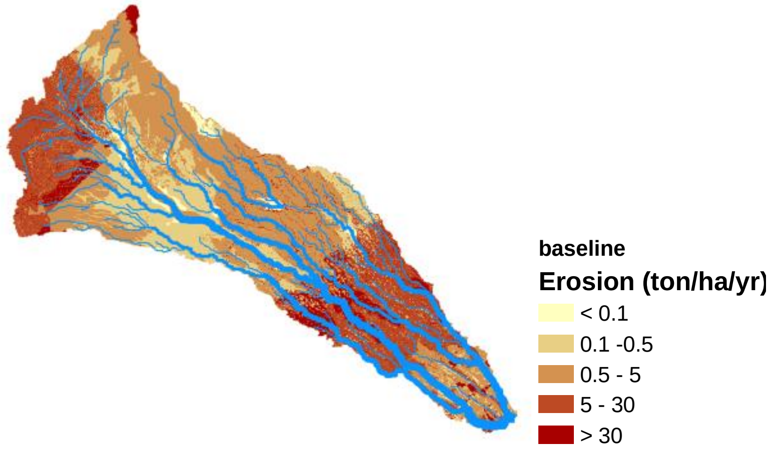

Figure 5-12. Average erosion rates for the baseline scenario (ton/ha/yr) for the Thika/Chania watershed

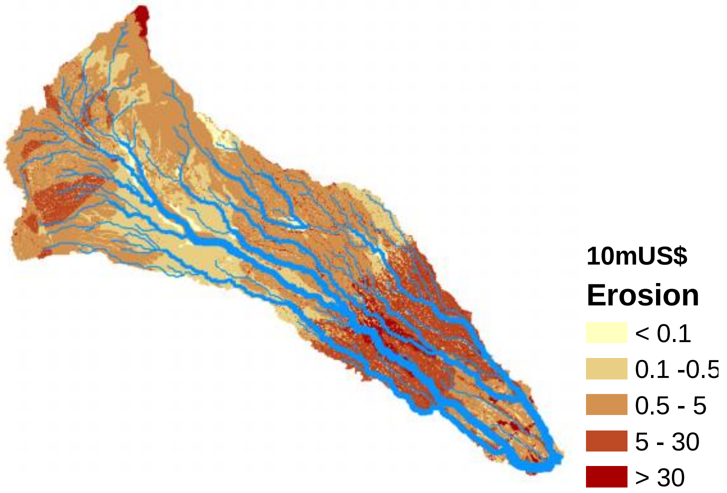

Figure 5-13. Average erosion rates for the 10 mUSD investment scenario (ton/ha/yr) for the Thika/Chania watershed

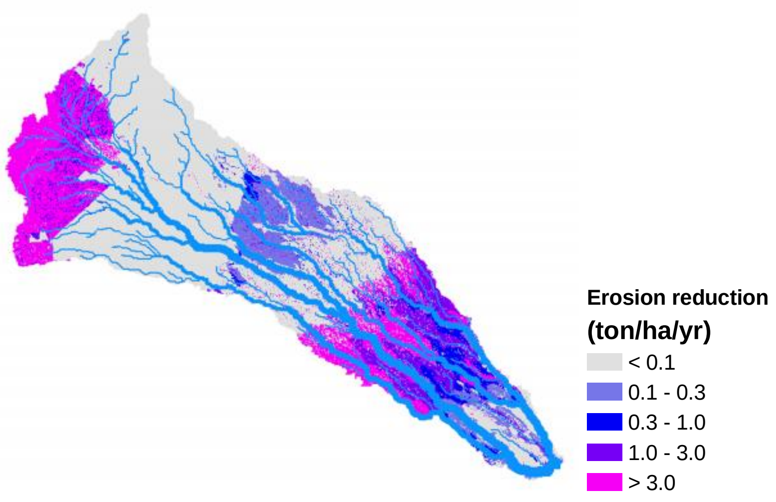

Figure 5-14. Erosion reduction for the 10 mUSD investment scenario (ton/ha/yr) for the Thika/Chania watershed

Table 5-3 shows the reduction in sediment yield for the scenarios in which half of the budget is invested upstream of the Nairobi water supply abstraction points. Most of the reductions can be attributed to activities taking place in the general agriculture areas and the mitigation activities for erosion from roads. No coffee is cultivated in the watershed provisioning water to Nairobi so reductions are zero. However for the investments in the entire watershed (Table 5-4) activities in the coffee zone cause significant reductions in sediment yield, even leading to the highest total reduction under the 15 mUS$ scenario.

Table 5-3. Average reduction (tons) in erosion coming from the principal land use classes where activities are planned for the part upstream of the Nairobi water supply abstraction points in the Thika/Chania watershed

Scenario	Degraded land	Coffee	General agriculture	Tea	Unpaved road	Total
1.25m$ N	-18,121	0	-31,486	-73	-21,728	-71,408
2.5m$ N	-18,419	0	-66,745	-676	-26,913	-112,753
5m$ N	-18,844	0	-140,709	-766	-34,438	-194,757
7.5m$ N	-19,288	0	-148,946	-1,505	-40,451	-210,190

Table 5-4. Average reduction (tons) in erosion coming from the principal land use classes where activities are planned for the entire Thika/Chania watershed

Scenario	Degraded land	Coffee	General agriculture	Tea	Unpaved road	Total
2.5mUS$	-52,278	-7,615	-54,926	-382	-102,205	-217,406
5mUS$	-53,325	-31,289	-116,192	-979	-119,352	-321,137
10mUS$	-53,818	-80,818	-179,220	-1,172	-126,577	-441,605
15mUS$	-54,149	-218,836	-186,397	-1,868	-140,153	-601,402

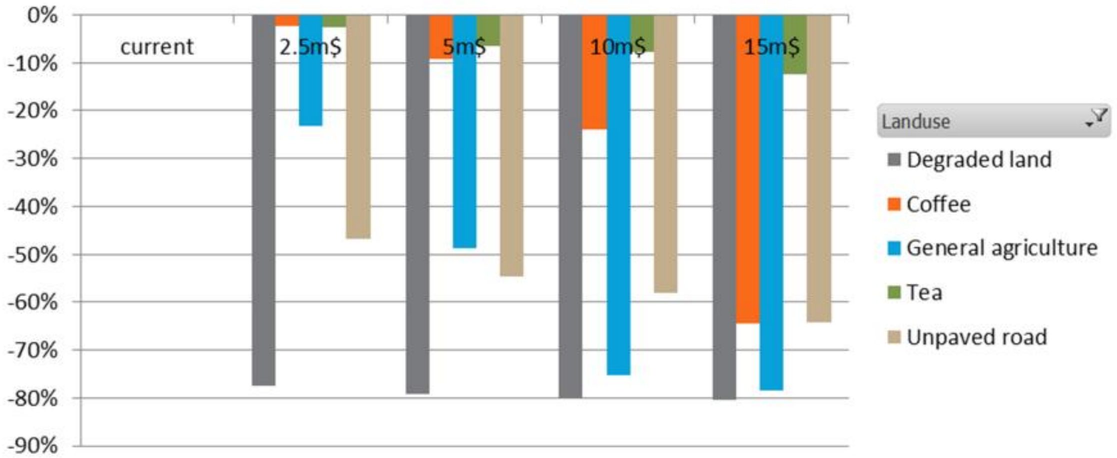

Figure 5-15. Average relative reduction (%) in erosion in the Thika/Chania watershed for the different investment scenarios compared to the current situation

6 Economic analysis upstream

6.1 Approach

Soil and water conservation measures have been studied in many parts of the world and agricultural and livelihoods benefits have been assessed quantitatively and qualitatively. A large database with qualitative estimates on the agricultural benefits is the WOCAT database [*WOCAT*, 2007]. Local studies also provided quantitative estimates of impact of land management activities. Table 6-1 provides a list of studies carried out in the Upper Tana or in very similar regions, where a certain agricultural practice was implemented and a quantitative estimate was done on the benefits on yield.

Table 6-1. Yield increase reported after implementing a certain agricultural practices in the Upper Tana or similar areas

Reference; area	Activity	Increase in yield (%)
[*Okoba and Sterk*, 2006b]; sub-humid Kenya	Various	50%
[*Araya and Stroosnijder*, 2010]; semi-arid Ethiopia	Tied ridges	40-60% in dry years
[*Okeyo et al.*, 2014]; sub-humid Kenya	Minimum tillage, mulching	5-7%
[*Enfors et al.*, 2011]; semi-arid Tanzania	Conservation tillage	40%
[*Miriti et al.*, 2012]; semi-arid Kenya	Tied ridges	30%
[*Tenge et al.*, 2005]; humid Tanzania	Grass strips; Bench terraces; Fanya Juu	25%; 50%; 35%
[*Teshome et al.*, 2013]; sub-humid Ethiopia	Fanya Juu	10-15%
[*Mucheru-Muna et al.*, 2010]; sub-humid Kenya	Intercropping	40%

The large variation in yield increase, even for the same activity indicates that the benefit is highly dependent on local biophysical conditions (climate, soil type, slope, crop type, etc) and on how the activity is exactly implemented (maintenance, combination with other best management practices, etc). The variability of the biophysical conditions can be taken into account when looking at the potential of soil and conservation practices, but still its success is highly dependent on the on-the-ground implementation and farmer support (technical and financial).

The main process behind the relationship between agricultural activities and yields is related to the conservation and accumulation of organic matter and water retention capacity in the upper soil horizon. There is a direct relation between thickness of the upper root zone of the crop and crop yield, as conceptually visualized in Figure 6-1a [*Mueller et al.*, 2010]. At the same time, comparing eroded and non-eroded fields, more technology and water input is required to obtain similar yields as represented in Figure 6-1b. The principal factors involved in this process are (i) soil water holding capacity, (ii) soil fertility, and (iii) soil structure.

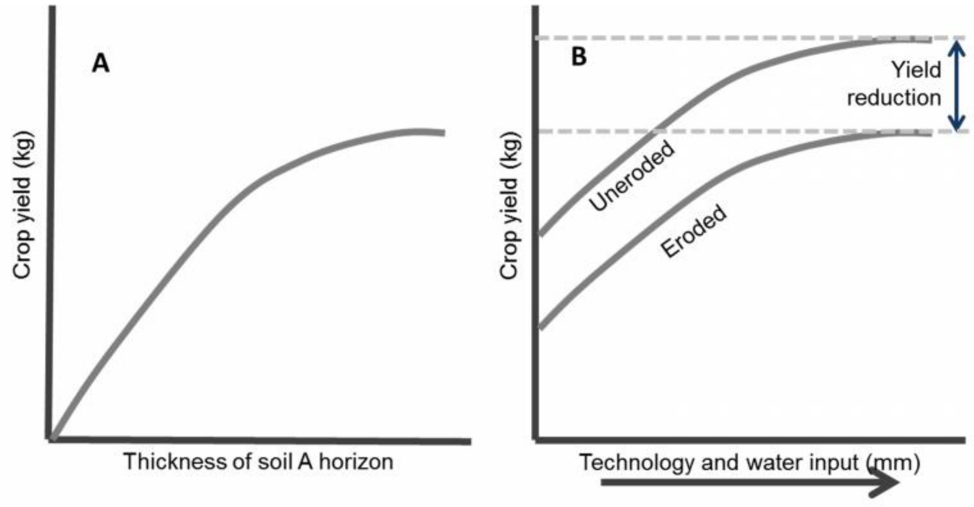

Figure 6-1. Impact of thickness of the upper soil horizon on crop yield (A) and the impact of erosion on technology and water input compared to crop yield (B) (adapted from [*Miller and Tidman*, 2001]**)**

Many studies have been done relating these three soil characteristics with soil productivity in qualitative way, and local studies exist also with quantitative results. Observed data on annual yield decline due to erosion is limited but in generally values around 2% for moderate erosion levels have been reported [*Hurni*, 1988; *Ellis-Jones and Tengberg*, 2000; *Posthumus and De Graaff*, 2005]. However, relative yield decline depend on the inherent soil productivity at each site. In the Upper Tana, about 55% of the respondents in the baseline survey [*Leisher et al.*, 2013] stated that their yields declined compared to 5 years ago.

More generic (empirical) relationships relating yield decline or soil productivity and erosion can been found [e.g. *Lindstrom et al.*, 1992; *Duan et al.*, 2011]. These researchers have used a productivity model with focus on soil erosion, called the Productivity Index (PI) model developed by Pierce et al. [1983] and slightly modified by Mulengera and Payton [1999] and Duan et al [2011]. The modified PI model equation is:

$$PI = \sum_{i=1}^{n} (A_i \cdot D_i \cdot O_i \cdot CL_i \cdot WF_i)$$

where Ai is sufficiency of soil water holding capacity in the ith layer, Di is sufficiency of soil pH, Oi is sufficiency of organic matter (OM), CLi is the sufficiency of clay (particle size <0.002 mm) content (%), WFi is the root weighting factor of the ith soil layer, and n is the number of soil layers of the root zone depth.

For this assessment the relevant terms of the equation are the available water capacity (Ai) and the organic matter content (Oi). These factors are calculated as follows:

$$A_i = \begin{cases} 0 \ldots\ldots\ldots AWC_i \le 0.03 \\ 5 \times AWC_i \ldots\ldots\ldots 0.03 < AWC_i \le 0.2 \\ 1 \ldots\ldots\ldots AWC_i > 0.2 \end{cases}$$

$$O_i = \begin{cases} \dfrac{OM_i}{4} \ldots\ldots\ldots 0\% \le OM_i < 4\% \\ 1 \ldots\ldots\ldots 4\% \le OM_i \end{cases}$$

The SOTER soil dataset of the Upper Tana region provides information on total available water (TAWC in mm/m) and organic carbon content (TOTC in g/kg) of the upper root layer. These values vary strongly in the catchment. This means that also the impact of erosion on soil productivity varies considerably within the catchments. This variability can be taken into account is sufficient data are available. The SOTER dataset is of relatively high detail and a good effort was done to produce soil physical information for each soil class. Therefore, this spatial information is taken into account in the upstream benefit analysis.

Table 6-2. Variability of total available water capacity and organic carbon content in Upper Tana based on SOTER dataset

	Total available water capacity (%)	Organic carbon content (g/kg)
Minimum	5	2.0
Average	15	16.1
Maximum	30	82.7

Thus, less erosion leads to the conservation of productive soil and organic matter. Several cases have demonstrated that it is possible to restore organic matter levels in the soil after their initial depletion. After investing in conservation agriculture the increase in biomass production can restore organic matter and even increase it to higher levels than before any agricultural activity took place (Figure 6-2).. This is due to a positive feedback process, in which active organic matter provides habitat and food for beneficial soil organisms that help build soil structure and porosity, providing nutrients to plants, and improve the water holding capacity of the soil. After a certain period of time, a new equilibrium is reached in the soil system.

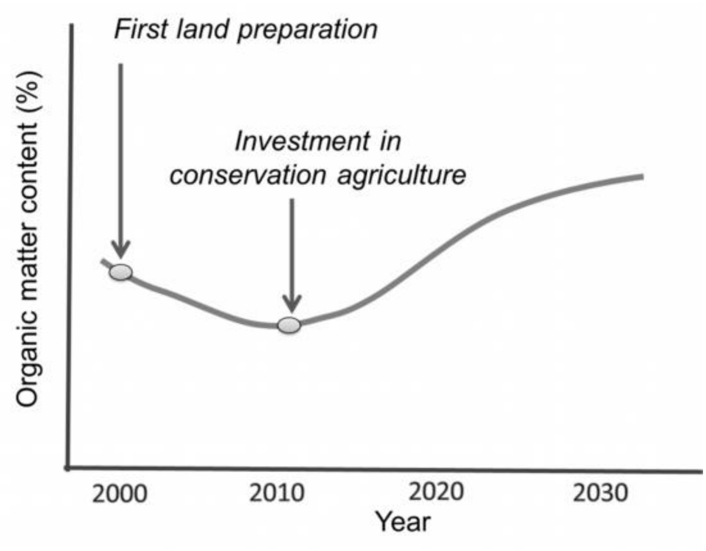

Figure 6-2. Example of the evolution of organic matter from first land preparation and after the implementation of soil and conservation activities (adapted from [*Bot and Benites*, 2005]**)**

The increase in soil productivity leads to higher productive biomass, more beneficial transpiration and less non-beneficial evaporation from soil and weeds. The reduction in soil evaporation leads to more soil water available for plant transpiration and infiltration to the sub-soil [e.g. *Rockström*, 2003; *Adgo et al.*, 2013]. The partitioning between transpiration and infiltration depends on the hydrological functioning of the system. Thus, investing in upstream agricultural best management practices may also lead to increased water infiltrating to the subsoil and thus to enhanced water supplies coming from the field.

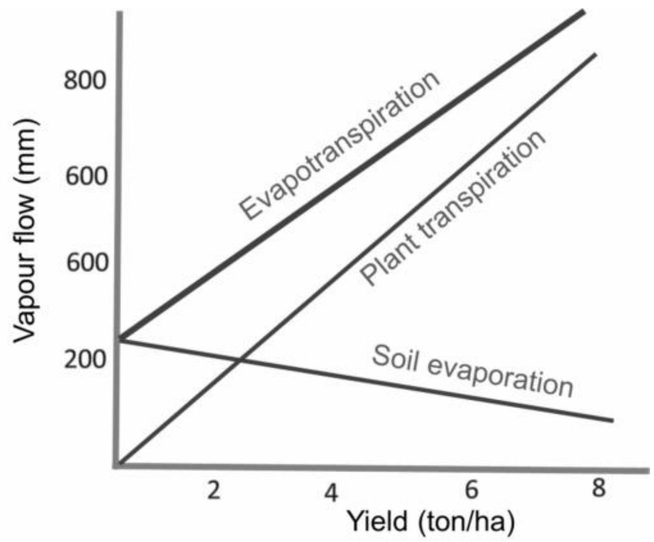

Figure 6-3. General relationship between crop yield and the two components of evapotranspiration: soil evaporation (including evapotranspiration of weeds, etc) and crop transpiration (adapted from [*Rockström*, 2003]**)**

The SWAT model provides predictions on soil loss reduction and on the soil water balance but does not dynamically model the complex processes and interactions that determine soil fertility changes on the long term. Therefore, the PI equation was used for to infer soil productivity changes, based on soil and land use data and SWAT outputs (soil erosion and evapotranspiration) causing a reduction in non-productive evaporation and thus an increase in crop transpiration and infiltration.

To translate this relative increase in crop transpiration to economic benefits a 1-step or a 2-step approach can be taken. The 2-step approach converts crop transpiration to yields (ton/ha) and then multiplies these yields with data on crop prices ($/ton). The 1-step approach uses economic water productivity coefficients: net economic benefits per unit of water ($/m3), that translate water use directly in an economic benefit. For this analysis, the 1-step approach was preferred to reduce the number of steps and related uncertainties.

Like most other economic data, economic water productivity coefficients depend very much on the geographic location. For this study, a recent publication on economic water footprints for Kenya was used that provides for the main crops economic water productivity values. The principal values for this study are shown in Table 6-3.

Table 6-3. Economic water productivity per crop type in the Upper Tana (from [*Mekonnen and Hoekstra*, 2014] **and** [*Leisher et al.*, 2013]**)**

Crop	Economic water productivity (US$/m3)
Coffee	0.09
Tea	0.43
Corn	0.09
General agriculture (corn, pulses and vegetables)	0.10
Fruits	0.57

For the different investment scenarios, the net economic benefits were calculated based on the economic water productivity for each of the crops was calculated for the three watersheds. Then, the difference between the productivity ($) of the investment scenarios with the baseline scenario gives an estimate of the change in revenue and thus an indication of the net benefit of the investment, per crop and watershed. This can be summarized as follows:

$$Revenue^{scenario} = \sum_{c} EWP_c \; * T_c^{scenario}$$

$$RevenueChange = Revenue^{scenario} - Revenue^{baseline}$$

In which EWP is the economic water productivity in US$/$m^3$, T is the crop transpiration in m^3 and *c* are the crop types included in the analysis.

6.2 Benefits upstream farmers

6.2.1 Overall results

Erosion reduction leads to more favourable soil properties in terms of soil fertility and water retention. Upstream farmers will therefore benefit through higher production and increases in revenues. These benefits can be quantified by the SWAT model. It predicts how much fertile, water-retaining soil can be saved and thus how far productivity can be increased after investing in soil and water conservations practices. The SWAT output was used to estimate the increased agricultural productivity under the different investment scenarios using the economic water productivity for each crop type.

Table 6-4 shows the total economic productivity for the three priority watersheds as was estimated based on the SWAT outputs. The difference between the baseline scenario and the investment scenario (here presented the 10 mUS$ scenario) gives the change in revenue of the investment. For each of the priority watershed this is around 1 mUS$ per year, so in total for all the watersheds 3 mUS$ a year. The last column presents the relative difference in total production of the scenario compared to the baseline.

Table 6-4. Annual revenue under baseline and 10mUS$ investment scenario, and change in revenue of investment

Watershed	Revenue baseline (US$m/yr)	Revenue 10mUS$ scenario (US$m/yr)	Change in revenue (US$m/yr)	Difference (%)
Sagana	64.0	64.8	0.8	1.3%
Maragua	50.4	51.2	0.8	1.7%
Thika/Chania	76.4	77.4	1.0	1.3%
Total	**190.7**	**193.4**	**2.7**	**1.4%**

From the last column in Table 6-4, it may appear that the relative difference in benefits is low. However, the total production corresponds to the total production of the entire watershed while the changes in agricultural income occur only in the areas where the activities take place. Table 6-5 shows the changes in revenue for the 10mUS$ scenario and how this translates to a change in revenue per hectare intervened (so surface where an activity is carried out). The values are shown for the main crop types, but summed for all the three priority watersheds. As can be seen the changes in revenue per hectare are substantial and in the same order of magnitude as the actual income per hectare for coffee and general agriculture.

Table 6-5. Annual changes in revenue of the 10 mUS$ investment scenario per crop type.

Landuse	Change in revenue (mUS$)	Total area with activities (ha)	Revenue change / ha (US$/ha)
Coffee	1.6	6281	247
General agriculture	0.8	13295	61
Tea	0.3	814	308

Table 6-6 shows per crop type and per watershed the predicted economic benefits for the 10 mUS$ scenario. As can be seen, especially in the Maragua watershed major benefits are obtained in the coffee fields. For the other watersheds, similar benefits are obtained in the general agricultural areas. The benefits are smaller for tea but are still reasonable compared to the total change in revenue that was estimated. In the Sagana watershed it is even similar to the benefits in coffee and general agriculture.

Table 6-6. Annual upstream benefits per watershed and crop type (million USD) for the 10 mUSD investment scenario

Watershed	General agriculture	Coffee	Tea	Total
Sagana	0.28	0.31	0.17	**0.76**
Maragua	0.09	0.70	0.04	**0.83**
Thika/Chania	0.43	0.54	0.05	**1.02**
Total upstream	**0.80**	**1.55**	**0.25**	**2.61**

Figure 6-4 shows the total benefits per watershed under the 4 different investment scenarios. Overall, the highest benefits are obtained in Thika/Chania. As can be seen, the total change in revenue of the 10mUS$ investment are more or less twice the benefits of the 5mUS$ investment for all watersheds. A more or less proportional increase is predicted for the 15mUS$ scenario for the Sagana and Maragua watershed. For the Thika/Chania watershed, the

15mUS$ includes the prioritization of additional coffee areas that cause significant additional benefits.

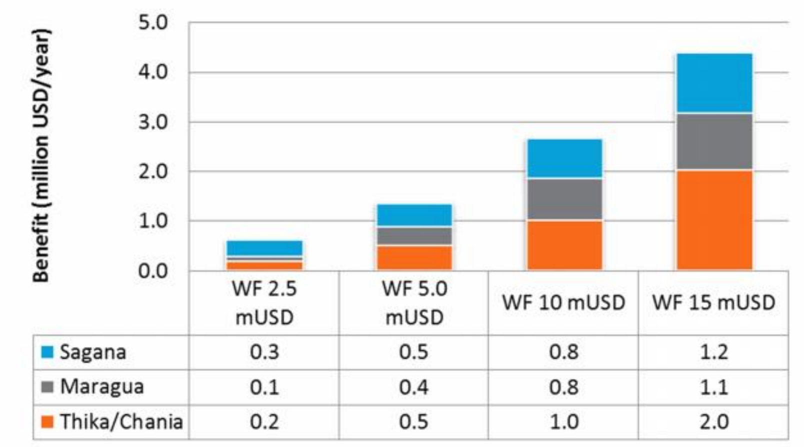

Figure 6-4. Annual upstream benefits per watershed for the 4 investment scenarios (in million USD)

Table 6-7 shows insight in how the benefits are likely to evolve over time after the investment. After a certain period of time (in this analysis around 10 years), benefits do not further increase significantly as a new equilibrium has been reached (see also Figure 6-2). This is because due to physical constraints, the soil productivity cannot further increase significantly anymore. For this assessment, the changes in revenue over a 10-year period were taken as this corresponds also to the time window of the overall analysis.

Table 6-7. Change in revenue over time (mUS$)

Scenario	After 5 year	After 10 year	After 15 year
current	0	0	0
2.5m$	0.34	0.60	0.63
5m$	0.74	1.32	1.50
10m$	1.46	2.60	3.14
15m$	2.40	4.31	5.35

Concluding, the long-term change in annual revenues that can be expected from soil preservation is approximately US$3 million per year after 10 years for the 10m$ investment scenario, levelling off slightly higher than that in the long run, as the soil reaches a new equilibrium state. However, because the economic water productivity statistics used are based on the sediment export value, not all of this increase in revenue amounts to a pure 'benefit' to farmers. Some of that value is captured elsewhere in the value chain, and there are also some additional costs associated with moving the increased yields through the value chain, which mean that the total benefit to the Kenyan economy is less than that figure suggests. Therefore, in the reference case for the ROI analysis, benefits are scaled down by 50% relative to revenue, to account for this issue. Even with this adjustment, these agricultural yield benefits comprise a major portion of benefits produced by the Water Fund.

6.2.2 Sagana watershed

Figure 6-5 shows the relative increase in yield in the Sagana watershed. Benefits concentrate around and upstream of Nyeri town mainly but also in the more downstream areas benefits are predicted. As expected, this corresponds to where the concentration of activities was proposed by the RIOS tool (see Figure 5-1).

Table 6-8 gives some more insight in how this translates to net economic benefits and how they break out per crop type and investment scenario. Most of the benefits can be attributed to the coffee areas. For the 10 mUS$ scenario, similar benefits are generated for the three principal crop types (around 0.26 mUS$/yr).

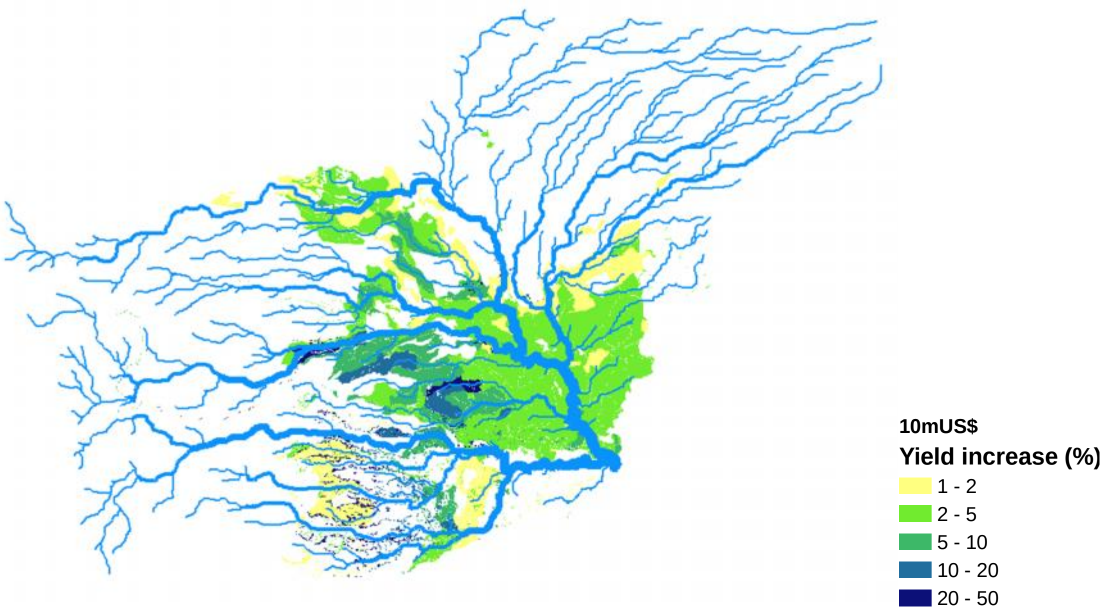

Figure 6-5. Relative yield increase under the 10 mUSD investment scenario for the Sagana watershed

Table 6-8. Change in revenue of investment scenarios (mUS$/yr) for the Sagana watershed and the main crop types

Scenario	Agro-forestry	Coffee	General agriculture	Tea	Total
2.5m$	0.00	0.14	0.07	0.08	0.29
5m$	0.00	0.18	0.14	0.10	0.42
10m$	0.00	0.30	0.26	0.17	0.73
15m$	0.00	0.55	0.40	0.18	1.13

6.2.3 Maragua watershed

Figure 6-6 shows the relative increase in crop production under the 10 mUS$ scenario. As can be seen most of the increase is predicted in the higher parts of the coffee zone. Table 6-9 confirms that most of the economic benefits will occur in the coffee areas. Also for the general agriculture and tea zone a significant change in revenue is predicted. For agroforestry and orchard fields the benefits are relatively small.

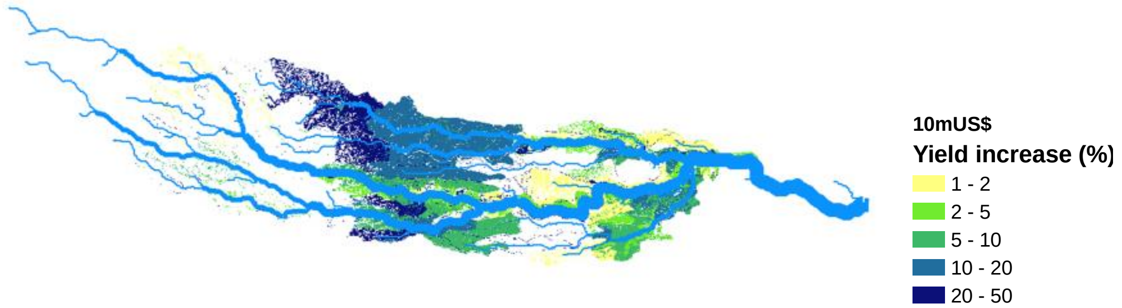

Figure 6-6. Relative yield increase under the 10 mUSD investment scenario for the Maragua watershed

Table 6-9. Change in revenue (mUS$/yr) of investment scenarios for the Maragua watershed and the main crop types

Scenario	Agro-forestry	Coffee	General agri-culture	Orchards	Tea	Total
2.5m$	0.00	0.08	0.01	0.00	0.01	0.10
5m$	0.00	0.31	0.04	0.01	0.02	0.37
10m$	0.00	0.70	0.08	0.01	0.04	0.84
15m$	0.00	0.90	0.12	0.04	0.06	1.13

6.2.4 Thika/Chania watershed

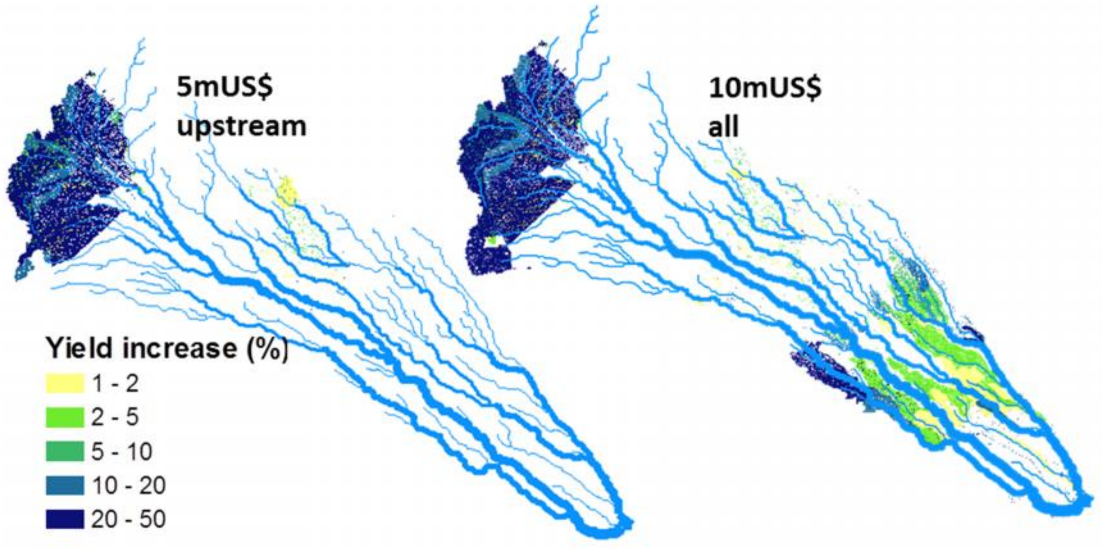

Figure 6-7 shows the maps for the predicted increase in production for the scenario in which all activities take place upstream of the Nairobi water supply abstraction points (left) and for the scenario in which the investment is spent in the entire watershed. For both scenarios the benefits concentrate in the higher part of the watershed where many activities will take place (principally grass strips). Under the 10mUS$ even more activities take place in these upstream areas making the benefits slightly higher. But the main difference between both scenarios can be seen in the downstream areas, where the coffee zone and also partly the tea zone is targeted.

Table 6-10 shows the economic benefits for the principal crops and the scenarios where the investment was targeted in the entire watershed. Under the 15 mUS$ the difference a relatively large additional change in revenue is predicted compared to the 10 mUS$ scenario in the coffee zone.

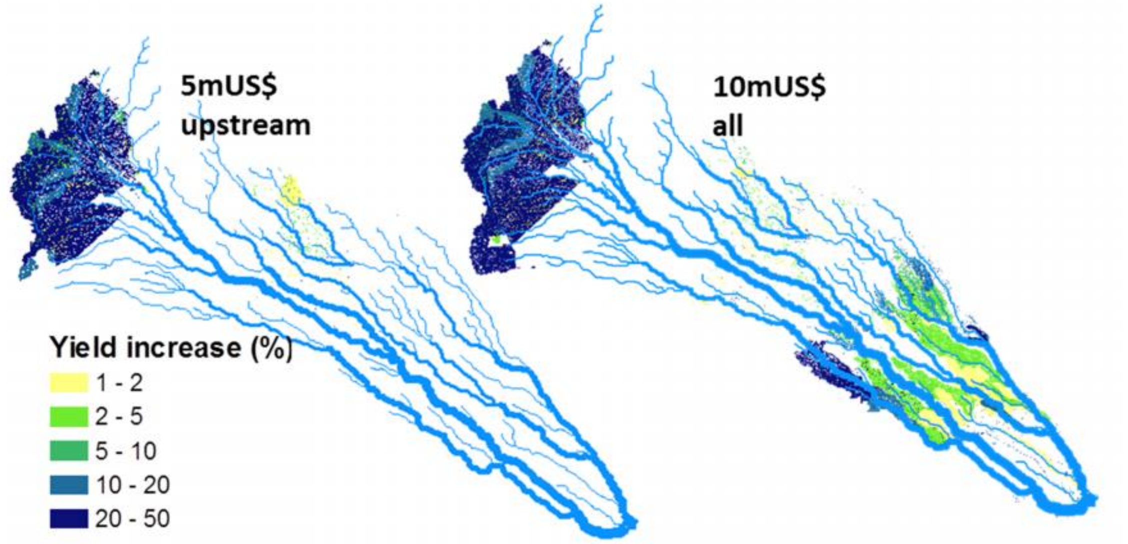

Figure 6-7. Relative yield increase under the 10 mUSD investment scenario for the Thika/Chania watershed

Table 6-10. Change in revenue (mUS$/yr) of investment scenarios for the Thika/Chania watershed and the main crop types

Scenario	Agro-forestry	Coffee	General agriculture	Orchard	Tea	Total
2.5m$	0.00	0.12	0.14	0.00	0.03	0.29
5m$	0.01	0.48	0.31	0.01	0.06	0.87
10m$	0.02	1.22	0.51	0.01	0.08	1.84
15m$	0.02	2.38	0.57	0.04	0.14	3.14

6.3 Sources of uncertainty

Cropping patterns in the Upper Tana basin are highly dynamic. Depending on market prices of farm inputs and outputs the crops and thus land management practices can sometimes change rapidly over time. Currently it is reported that due to a lower tea prices, some farmers in the tea zone start cultivating pineapple instead of tea. It is evident that this conversion can lead to high rates of erosion. The conversion and land preparation itself, but also even during the growing season pineapples on steep slopes can cause serious erosion. This continuously changing landscape has to take into account when considering the final conclusion of this business study. It is important to continuously monitor farmers' practices and cropping patterns through the extension services and potentially also remote sensing.

Other highly variable point sources of sediments in the Upper Tana basin are the quarries. Some of them have licenses and do have mitigation measures that limit the sediment generation. The illegal ones however lack often any mitigation measure and can cause serious point sources of sediment. Also these features in the landscape need to be monitored and measures need to be taken. These point sources were not taken into account in this business case study.

Besides there are some other sources of uncertainty that are related to the modelling approach:

- Issues related to the spatial scale of the input data. The land use map was available on a relatively high scale (15 meter resolution) and with a good accuracy. Data on elevation, soil and meteorological data were available with less spatial detail, but the best available datasets were used.

- The proposed activities are in fact a combination of several infrastructural measures and agricultural practices. Obviously, the implementation of them depends highly on each site, farmer and other factors. For this reason, the parameterization of the activities in RIOS and SWAT is not straight-forward and requires expert judgement.

- Data on erosion and sediment dynamics is generally very poor, not only in the Upper Tana basin. At the same time, without no doubt erosion and sediment transport can be considered one of the most complex hydrological processes, with many non-linearities and relations that depend highly on their location in time (seasonality, etc) and space. The modelling equations to capture sediment dynamics are therefore generally also prone to a relative high level of uncertainty.

- Relating erosion with agricultural productivity requires many years of measurements and field data, so long-term projects that are relatively costly. Also, these relationships are again highly dependent on a wide range of biophysical conditions and many of them are hard to control and variable in time. This means that the relationships between erosion and agricultural productivity are purely empirical and based on few ground-truth data. Additional uncertainty comes in when doing an economic assessment as prices of agricultural products are highly volatile.

In spite of this uncertainty, it should be considered that the goal of the Business case study is to assess the biophysical and economic viability of the investments on the watershed level and for long-term implementation. It is clear that when aggregating in space and time part of the above mentioned uncertainties are reduced. We believe that in spite of the uncertainties the analysis provides sufficient evidence that the Water Fund can be a useful mechanism to enhance the ecosystem services that upstream farmers and downstream water users rely on.

7 Conclusions

7.1 Main findings

This report summarizes results of the biophysical impact assessment to support the Business Case study of the Upper Tana River – Nairobi Water Fund. The model SWAT was used to convert the investment portfolios of the RIOS tool (where to do what) into quantifiable impacts (erosion, turbidity, flows). Various investment levels were analyzed for the selected priority watersheds (Sagana, Maragua and Thika/Chania).

The results show significant erosion reductions in the agricultural areas, mainly for the coffee areas and the degraded land areas. For the unpaved roads, also significant reductions in erosion can be expected. The impact on other agricultural lands depends highly on the implementation intensity and prevailing biophysical setting. In general significant reductions in erosion can be achieved in many points across the watersheds by implementing a mix of activities.

The long-term change in annual revenues that can be expected from soil conservation investments is approximately US$3 million per year after 10 years, levelling off slightly higher than that in the long run, as the soil reaches a new equilibrium state. Even taking into account that a significant part of this revenue change will be captured elsewhere in the value chain and not by the farmers themselves, these yield benefits comprise a major portion of benefits produced by the Water Fund. More conclusions on how these benefits fit in the overall Return On Investment analysis can be found in the main business case report [*TNC*, 2015].

7.2 Potential future analysis steps

Some possible future analysis and modelling assessments are summarized here, that can further support the development and implementation of the Nairobi Water Fund:

- The launched monitoring scheme will provide more insight in the sediment dynamics of the watersheds. This new data will have to be assimilated in the modelling tools to further support the implementation and predict impacts on sites that are not monitored, or variables that cannot be monitored. The inclusion of remote sensing technology (satellites and airborne) can be considered as this technology is increasingly cost-effective for this type of monitoring programmes.

- To increase the robustness of the analysis, a wider range of RIOS portfolios and SWAT impact assessments can be carried out, to bound better the uncertainties involved. Special focus can be put on the parameterization of the activities in RIOS and SWAT and non-linearities that arise from spatial targeting issues.

More details on next steps in the implementation of the Water Fund can be found in the main business case report [*TNC*, 2015].

9 References

Adgo, E., A. Teshome, and B. Mati (2013), Impacts of long-term soil and water conservation on agricultural productivity: The case of Anjenie watershed, Ethiopia, *Agric. Water Manag.*, *117*, 55–61, doi:10.1016/j.agwat.2012.10.026.

Angima, S. ., D. . Stott, M. . O'Neill, C. . Ong, and G. . Weesies (2003), Soil erosion prediction using RUSLE for central Kenyan highland conditions, *Agric. Ecosyst. Environ.*, *97*(1), 295–308, doi:10.1016/S0167-8809(03)00011-2.

Angima, S. D., D. E. Stott, M. K. O'Neill, C. K. Ong, and G. A. Weesies (2002), Use of calliandra–Napier grass contour hedges to control erosion in central Kenya, *Agric. Ecosyst. Environ.*, *91*(1-3), 15–23, doi:10.1016/S0167-8809(01)00268-7.

Arabi, M., J. R. Frankenberger, B. A. Engel, and J. G. Arnold (2008), Representation of agricultural conservation practices with SWAT, *Hydrol. Process.*, *22*(16), 3042–3055, doi:10.1002/hyp.6890.

Araya, A., and L. Stroosnijder (2010), Effects of tied ridges and mulch on barley (Hordeum vulgare) rainwater use efficiency and production in Northern Ethiopia, *Agric. Water Manag.*, *97*(6), 841–847, doi:10.1016/j.agwat.2010.01.012.

Bagnold, R. A. (1977), Bed load transport by natural rivers, *Water Resour. Res.*, *13*(2), 303–312, doi:10.1029/WR013i002p00303.

Batjes, N. H. (2010), *Soil property estimates for the Upper Tana , Kenya , derived from SOTER and WISE*, Wageningen, Netherlands.

Bennett, N. D. et al. (2013), Characterising performance of environmental models, *Environ. Model. Softw.*, *40*, 1–20, doi:10.1016/j.envsoft.2012.09.011.

Betrie, G. D., Y. a. Mohamed, a. van Griensven, and R. Srinivasan (2011), Sediment management modelling in the Blue Nile Basin using SWAT model, *Hydrol. Earth Syst. Sci.*, *15*(3), 807–818, doi:10.5194/hess-15-807-2011.

Bot, A., and J. Benites (2005), The importance of soil organic matter, *FAO Soils Bull.*, 1–80, doi:10.1080/03650340214162.

Brown, T., and H. Schneider (1996), Multi-scale estimates of erosion and sediment yields in the Upper Tana basin , Kenya, *Victoria*, (236), 49–54.

Brown, T., H. Schneider, and D. Harper (1996), Multi-scale estimates of erosion and sediment yields in the Upper Tana basin, Kenya, *IAHS Publ. Proc. Reports-Intern Assoc Hydrol. Sci.*, *236*, 49–54.

Condon, L. E., and R. M. Maxwell (2014), Feedbacks between managed irrigation and water availability: Diagnosing temporal and spatial patterns using an integrated hydrologic model, *Water Resour. Res.*, n/a–n/a, doi:10.1002/2013WR014868.

Diebel, M. W., J. T. Maxted, P. J. Nowak, and M. J. Vander Zanden (2008), Landscape planning for agricultural nonpoint source pollution reduction I: a geographical allocation framework., *Environ. Manage.*, *42*(5), 789–802, doi:10.1007/s00267-008-9186-3.

Duan, X., Y. Xie, T. Ou, and H. Lu (2011), Effects of soil erosion on long-term soil productivity in the black soil region of northeastern China, *CATENA*, *87*(2), 268–275, doi:10.1016/j.catena.2011.06.012.

Dunne, T. (1979), Sediment yield and land use in tropical catchments, *J. Hydrol.*, *42*(3), 281–300.

Ellis-Jones, J., and A. Tengberg (2000), The impact of indigenous soil and water conservation practices on soil productivity: examples from Kenya, Tanzania and Uganda, *L. Degrad. Dev.*, *11*(1), 19–36, doi:10.1002/(SICI)1099-145X(200001/02)11:1<19::AID-LDR357>3.0.CO;2-2.

Enfors, E., J. Barron, H. Makurira, J. Rockström, and S. Tumbo (2011), Yield and soil system changes from conservation tillage in dryland farming: A case study from North Eastern Tanzania, *Agric. Water Manag.*, *98*(11), 1687–1695, doi:10.1016/j.agwat.2010.02.013.

Giri, S., A. P. Nejadhashemi, S. Woznicki, and Z. Zhang (2014), Analysis of best management practice effectiveness and spatiotemporal variability based on different targeting strategies, *Hydrol. Process.*, *28*(3), 431–445, doi:10.1002/hyp.9577.

Guto, S. N., P. Pypers, B. Vanlauwe, N. de Ridder, and K. E. Giller (2011), Tillage and vegetative barrier effects on soil conservation and short-term economic benefits in the Central Kenya highlands, *F. Crop. Res.*, *122*(2), 85–94.

Guto, S. N., N. de Ridder, K. E. Giller, P. Pypers, and B. Vanlauwe (2012), Minimum tillage and vegetative barrier effects on crop yields in relation to soil water content in the Central Kenya highlands, *F. Crop. Res.*, *132*, 129–138, doi:10.1016/j.fcr.2011.10.014.

Hunink, J. E., and P. Droogers (2011), *Physiographical baseline survey for the Upper Tana catchment : erosion and sediment yield assessment*, Report FutureWater 112.

Hunink, J. E., P. Droogers, S. Kauffman, B. M. Mwaniki, and J. Bouma (2012a), Quantitative simulation tools to analyze up- and downstream interactions of soil and water conservation measures : Supporting policy making in the Green Water Credits program of Kenya, *J. Environ. Manage.*, *111*, 187–194.

Hunink, J. E., P. Droogers, S. Kauffman, B. M. Mwaniki, and J. Bouma (2012b), Quantitative simulation tools to analyze up- and downstream interactions of soil and water conservation measures: supporting policy making in the Green Water Credits program of Kenya., *J. Environ. Manage.*, *111*, 187–94, doi:10.1016/j.jenvman.2012.07.022.

Hunink, J. E., I. a. Niadas, P. Antonaropoulos, P. Droogers, and J. de Vente (2013), Targeting of intervention areas to reduce reservoir sedimentation in the Tana catchment (Kenya) using SWAT, *Hydrol. Sci. J.*, *58*(3), 600–614, doi:10.1080/02626667.2013.774090.

Hurni, H. (1988), Degradation and conservation of the resources in the Ethiopian highlands, *Mt. Res. Dev.*, 123–130.

Jothityangkoon, C., C. Hirunteeyakul, K. Boonrawd, and M. Sivapalan (2013), Assessing the impact of climate and land use changes on extreme floods in a large tropical catchment, *J. Hydrol.*, *490*, 88–105, doi:10.1016/j.jhydrol.2013.03.036.

Julien, P. Y. (2010), *Erosion and sedimentation*, Cambridge University Press.

Jungerius, P. D., J. Matundura, and J. A. M. van de Ancker (2002), Road construction and gully erosion in West Pokot, Kenya, *Earth Surf. Process. Landforms*, *27*(11), 1237–1247, doi:10.1002/esp.423.

Kauffman, S., P. Droogers, E. Odada, P. Macharia, P. Gicheru, and K. Dijkshoorn (2007), *Green and blue water resources and assessment of soil and water management scenarios using an integrated modelling framework. Green Water Credits Report 3*, Wageningen.

Kauffman, S., P. Droogers, J. Hunink, B. Mwaniki, F. Muchena, P. Gicheru, P. Bindraban, D. Onduru, R. Cleveringa, and J. Bouma (2014), Green Water Credits – exploring its potential to enhance ecosystem services by reducing soil erosion in the Upper Tana basin, Kenya, *Int. J. Biodivers. Sci. Ecosyst. Serv. Manag.*, 1–11, doi:10.1080/21513732.2014.890670.

Kinsey-Henderson, A. E., and S. N. Wilkinson (2013), Evaluating Shuttle radar and interpolated DEMs for slope gradient and soil erosion estimation in low relief terrain, *Environ. Model. Softw.*, *40*, 128–139.

Leisher, C. (2013), *Maragua and Thika / Chania Baseline Survey for the Upper Tana Water Fund*.

Leisher, C., C. Science, and T. N. Conservancy (2013), Maragua and Thika / Chania Baseline Survey for the Upper Tana Water Fund, , (February).

Lin, S., C. Jing, V. Chaplot, X. Yu, Z. Zhang, N. Moore, and J. Wu (2010), Effect of DEM resolution on SWAT outputs of runoff, sediment and nutrients, *Hydrol. Earth Syst. Sci. Discuss.*, *7*(4), 4411–4435, doi:10.5194/hessd-7-4411-2010.

Lindstrom, M. J., T. E. Schumacher, A. J. Jones, and C. Gantzer (1992), Productivity index model comparison for selected soils in North Central United States, *J. Soil Water Conserv.*, *47*(6), 491–494.

Maeda, E. E., P. K. E. Pellikka, M. Siljander, and B. J. F. Clark (2010), Potential impacts of agricultural expansion and climate change on soil erosion in the Eastern Arc Mountains of Kenya, *Geomorphology*, *123*(3), 279–289.

Mati, B. M., R. P. Morgan, F. N. Gichuki, J. N. Quinton, T. R. Brewer, and H. P. Liniger (2000), Assessment of erosion hazard with the USLE and GIS: A case study of the Upper Ewaso Ng'iro North basin of Kenya, *Int. J. Appl. Earth Obs. Geoinf.*, *2*(2), 78–86.

Mekonnen, M. M., and A. Y. Hoekstra (2014), Water conservation through trade: the case of Kenya, *Water Int.*, *39*(4), 451–468, doi:10.1080/02508060.2014.922014.

Miller, G., and M. Tidman (2001), Impact of Soil Erosion on Soil Productivity, *Integr. Crop Manag.*, *IC-486*(1), 3–4.

Miriti, J. M., G. Kironchi, A. O. Esilaba, L. K. Heng, C. K. K. Gachene, and D. M. Mwangi (2012), Yield and water use efficiencies of maize and cowpea as affected by tillage and cropping systems in semi-arid Eastern Kenya, *Agric. Water Manag.*, *115*, 148–155, doi:10.1016/j.agwat.2012.09.002.

Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith (2007), Model Evaluation Guidelines for Systematic Quantification of Accuraccy in Watershed Simulations, *Trans. Asabe*, *50*, 885–900, doi:10.13031/2013.23153.

Moriasi, D. N., J. L. Steiner, and J. G. Arnold (2011), Sediment measurement and transport modeling: impact of riparian and filter strip buffers., *J. Environ. Qual.*, *40*(3), 807–14, doi:10.2134/jeq2010.0066.

Mucheru-Muna, M., P. Pypers, D. Mugendi, J. Kung'u, J. Mugwe, R. Merckx, and B. Vanlauwe (2010), A staggered maize–legume intercrop arrangement robustly increases crop yields and economic returns in the highlands of Central Kenya, *F. Crop. Res.*, *115*(2), 132–139, doi:10.1016/j.fcr.2009.10.013.

Mueller, L., U. Schindler, W. Mirschel, T. G. Shepherd, B. C. Ball, K. Helming, J. Rogasik, F. Eulenstein, and H. Wiggering (2010), Assessing the productivity function of soils. A review, *Agron. Sustain. Dev.*, *30*(3), 601–614, doi:10.1051/agro/2009057.

Mulengera, M. K., and R. W. Payton (1999), Modification of the productivity index model, *Soil Tillage Res.*, *52*(1-2), 11–19, doi:10.1016/S0167-1987(99)00022-7.

Mwangi, H. M. (2011), *Evaluation of the impacts of soil and water conservation practices on ecosystem services in Sasumua watershed, Kenya, using SWAT model*, MSc Thesis Jomo Kenyatta University of Agriculture and Technology.

Neitsch, S. L., J. G. Arnold, J. R. Kiniry, J. R. Williams, and K. W. King (2005), Soil Water Assessment Tool (SWAT) Theoretical Documentation, *Blackl. Res. Center, Temple, TX*.

Nyssen, J., J. Poesen, J. Moeyersons, E. Luyten, M. Veyret-Picot, J. Deckers, M. Haile, and G. Govers (2002), Impact of road building on gully erosion risk: a case study from the Northern Ethiopian Highlands, *Earth Surf. Process. Landforms*, *27*(12), 1267–1283, doi:10.1002/esp.404.

Okeyo, A. I., M. Mucheru-Muna, J. Mugwe, K. F. Ngetich, D. N. Mugendi, J. Diels, and C. A. Shisanya (2014), Effects of selected soil and water conservation technologies on nutrient losses and maize yields in the central highlands of Kenya, *Agric. Water Manag.*, *137*, 52–58, doi:10.1016/j.agwat.2014.01.014.

Okoba, B. O., and G. Sterk (2006a), Farmers' identification of erosion indicators and related erosion damage in the Central Highlands of Kenya, *Catena*, *65*(3), 292–301, doi:10.1016/j.catena.2005.12.004.

Okoba, B. O., and G. Sterk (2006b), Quantification of visual soil erosion indicators in Gikuuri catchment in the central highlands of Kenya, *Geoderma*, *134*(1-2), 34–47, doi:10.1016/j.geoderma.2005.08.013.

Okoba, B. O., and G. Sterk (2010), Catchment-level evaluation of farmers' estimates of soil erosion and crop yield in the Central Highlands of Kenya, *L. Degrad. Dev.*, *21*(4), 388–400, doi:10.1002/ldr.1003.

Ongwenyi, G. S., S. M. Kithiia, and F. O. Denga (1993), An overview of the soil erosion and sedimentation problems in Kenya,

Owino, J., and R. Gretzmacher (2002), Performance of narrow strips of Vetiver grass (Vetiveria zizanioides) and Napier Grass (Pennisetum purpureum) as barriers against runoff and soil loss on a clay loam soil in Kenya, in *Proceedings of conference on international agricultural research development held at Deutscher, Tropentag, Witzenhausen*.

Parajuli, P. B., K. R. Mankin, and P. L. Barnes (2008), Applicability of targeting vegetative filter strips to abate fecal bacteria and sediment yield using SWAT, *Agric. Water Manag.*, *95*(10), 1189–1200, doi:10.1016/j.agwat.2008.05.006.

Pierce, F. J., W. E. Larson, R. H. Dowdy, and W. A. P. Graham (1983), Productivity of soils: Assessing long-term changes due to erosion, *J. Soil Water Conserv.*, *38*(1), 39–44.

Posthumus, H., and J. De Graaff (2005), Cost-benefit analysis of bench terraces, a case study in Peru, *L. Degrad. Dev.*, *16*(1), 1–11, doi:10.1002/ldr.637.

Rahman, M. R., Z. H. Shi, and C. Chongfa (2009), Soil erosion hazard evaluation—An integrated use of remote sensing, GIS and statistical approaches with biophysical parameters towards management strategies, *Ecol. Modell.*, *220*(13), 1724–1734.

Renard, K. G., G. R. Foster, G. A. Weesies, D. K. McCool, D. C. Yoder, and others (1997), Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE)., *Agric. Handb.*, (703).

Rockström, J. (2003), Water for food and nature in drought-prone tropics: vapour shift in rain-fed agriculture., *Philos. Trans. R. Soc. Lond. B. Biol. Sci.*, *358*(1440), 1997–2009, doi:10.1098/rstb.2003.1400.

Tenge, A. J., J. De graaff, and J. P. Hella (2005), Financial efficiency of major soil and water conservation measures in West Usambara highlands, Tanzania, *Appl. Geogr.*, *25*(4), 348–366, doi:10.1016/j.apgeog.2005.08.003.

Teshome, A., D. Rolker, and J. de Graaff (2013), Financial viability of soil and water conservation technologies in northwestern Ethiopian highlands, *Appl. Geogr.*, *37*, 139–149, doi:10.1016/j.apgeog.2012.11.007.

TNC (2015), *Upper Tana-Nairobi Water Fund Business Case*, The Nature Conservancy: Nairobi, Kenya.

Tuppad, P., N. Kannan, R. Srinivasan, C. G. Rossi, and J. G. Arnold (2010a), Simulation of Agricultural Management Alternatives for Watershed Protection, *Water Resour. Manag.*, *24*(12), 3115–3144, doi:10.1007/s11269-010-9598-8.

Tuppad, P., K. R. Douglas-Mankin, and K. A. McVay (2010b), Strategic targeting of cropland management using watershed modeling, *Agric. Eng. Int. CIGR J.*, *12*(3-4), 12–24.

De Vente, J., J. Poesen, G. Govers, and C. Boix-Fayos (2009), The implications of data selection for regional erosion and sediment yield modelling, *Earth Surf. Process. Landforms*, *34*(15), 1994–2007, doi:10.1002/esp.1884.

Walling, D. E., B. W. Webb, and J. C. Woodward (1992), Some sampling considerations in the design of effective strategies for monitoring sediment-associated transport, *Eros. sediment Transp. Monit. Program. river basins*, *210*, 279–288.

Wang, G., P. Hapuarachchi, H. Ishidaira, A. S. Kiem, and K. Takeuchi (2008), Estimation of Soil Erosion and Sediment Yield During Individual Rainstorms at Catchment Scale, *Water Resour. Manag.*, *23*(8), 1447–1465, doi:10.1007/s11269-008-9335-8.

White, M. J., D. E. Storm, P. R. Busteed, S. H. Stoodley, and S. J. Phillips (2009), Evaluating nonpoint source critical source area contributions at the watershed scale., *J. Environ. Qual.*, *38*(4), 1654–63, doi:10.2134/jeq2008.0375.

Williams, J. . (1995), The EPIC model, in *Computer Models of Watershed Hydrology*, edited by V. P. Singh, pp. 909–1000., Colorado, USA.

Williams, J. R. (1975), Sediment routing for agricultural watersheds, *J. Am. Water Resour. Assoc.*, *11*(5), 965–974.

Williams, J. R. (1980), SPNM, A MODEL FOR PREDICTING SEDIMENT, PHOSPHORUS, AND NITROGEN YIELDS FROM AGRICULTURAL BASINS, *J. Am. Water Resour. Assoc.*, *16*(5), 843–848, doi:10.1111/j.1752-1688.1980.tb02497.x.

Wischmeier, W. H., and D. D. Smith (1978), *Predicting rainfall erosion losses - A guide to conservation planning.*, Agricultur., US Department of Agriculture, Washington, DC.

WOCAT (2007), *Where the Land is Greener--Case Studies and Analysis of Soil and Water Conservation Initiatives Worldwide*, edited by H. Liniger and W. Critchley.

Wu, Y., and J. Chen (2012), Modeling of soil erosion and sediment transport in the East River Basin in southern China., *Sci. Total Environ.*, *441*, 159–68, doi:10.1016/j.scitotenv.2012.09.057.

Z&A (2011), *Physiographical Baseline Survey for the Upper Tana Catchment Area*, Nairobi, Kenya.

Ziegler, A. D., T. W. Giambelluca, R. A. Sutherland, M. A. Nullet, S. Yarnasarn, J. Pinthong, P. Preechapanya, and S. Jaiaree (2004), Toward understanding the cumulative impacts of roads in upland agricultural watersheds of northern Thailand, *Agric. Ecosyst. Environ.*, *104*(1), 145–158, doi:10.1016/j.agee.2004.01.012.