Integrated modelling for economic valuation of the role of forests and woodlands in drinking water provision to two African cities

*Biniam B. Ashagre [1], Philip J. Platts [2,3], Marco Njana [4], Neil D. Burgess [5,6], Andrew Balmford[7], Kerry Turner [8], Marije Schaafsma [9]**

[1] Centre for Water Systems, University of Exeter, Exeter, EX4 4QF, UK
[2] Environment Department, University of York, Heslington, York, YO10 5NG, UK
[3] Department of Biology, University of York, Heslington, York, YO10 5DD, UK
[4] National Carbon Monitoring Centre, Sokoine University of Agriculture, Morogoro, Tanzania
[5] UN Environment World Conservation Monitoring Centre (UNEP-WCMC), Cambridge, CB3 0DL, UK
[6] CMEC, The Natural History Museum, University of Copenhagen, Denmark
[7] Department of Zoology, University of Cambridge, Cambridge CB2 3EJ, UK
[8] School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, UK
[9] Geography and Environment, University of Southampton, Southampton, SO17 1BJ, UK
* corresponding author: M.Schaafsma@soton.ac.uk

Abstract
Rapidly growing economies often have high population growth, resulting in agricultural expansion in rural areas and increased water demand in urban areas. Conversion of forests and woodlands to agriculture may threaten safe and reliable water supply in cities. This study assesses the regulating functions and economic values of forests and woodlands in meeting the water needs of two major cities in Tanzania and proposes an integrated modelling approach with a scenario-based analysis to estimate costs of water supply avoided by forest conservation. We use the process-based hydrological Soil and Water Assessment Tool (SWAT) to simulate the role of woody habitats in the regulation of hydrological flow and sediment control. We find that the forests and woodlands play a significant role in regulating sediment load in rivers and reducing peak flows, with implications for the water supply from the Ruvu River to Dar es Salaam and Morogoro. A cost-based value assessment under water treatment works conditions up to 2016 suggests that water supply failure due to deforestation would cost Dar es Salaam USD 4.6-17.6 million per year and Morogoro USD 308 thousand per year. Stronger enforcement of forest and woodland protection in Tanzania must balance water policy objectives and food security.

Keywords
Ecosystem services, SWAT, Tanzania, soil erosion, urban water demand, land use

Highlights

- Forests and woodlands help to regulate seasonal flow and water provision
- We integrate hydrological and economic models to assess the value of water regulation
- Uncontrolled deforestation would result in higher household costs - especially for poorer people
- Conservation of forests would help meet water demand in Tanzania's large cities

1. Introduction

Africa has experienced a rapid increase in urban population in the last 20 years (Brikké and Vairavamoorthy 2016), driven by the combined effects of natural increase and rural-to-urban migration (Anderson et al. 2013, Dos Santos et al. 2017). It is expected that by 2040, 50% of the African population will live in cities (AfDB et al. 2014). In addition, economic growth is likely to increase water demand by a rate higher than population growth alone (Cole 2004). These developments will create significant pressure on existing, aging infrastructure and services including water (Larsen et al. 2016). Many cities depend on natural habitat and climatic conditions in upstream areas to deliver water through river systems (McDonald et al. 2013). At the same time, this urbanisation process puts additional pressure on catchments and regional natural habitats (Cumming et al. 2014). For example, many citizens in Sub-Saharan Africa still rely on catchment forests as their main source of energy, charcoal, creating a negative feedback effect on their water supply.

These dynamic urban-rural linkages, furthermore found in the supply of food, timber and other goods and the exchange and movement of people and information, call for a catchment approach to sustainable land-use planning. Land management has often aimed to improve services other than water quality or quantity, sometimes resulting in problems of supply and pollution (Brauman 2015). Modelling how land-use change affects downstream ecosystem services flows under different scenarios helps to anticipate and mitigate unintended consequences (Haase and Tötzer 2012). Although the impact of forests and woodlands on water quantity has been heavily debated (Bruijnzeel 2004, Sahin and Hall 1996), it has been argued that the removal of these woody habitats from upslope catchments and their replacement by agriculture affects flow patterns and water quality downstream, varying with the biophysical characteristics of the forests (Ponette-Gonzalez et al. 2015, Salman and Martinez 2015). For example, reduced river flow in the dry seasons can affect ecosystem services benefits such as drinking water and hydropower provision, while higher flow rates in the wet seasons can increase the risk of flooding and soil erosion (Cui et al. 2007, Ellison et al. 2012). The potentially higher proportion of direct overland runoff in the absence of woody vegetation can affect water supply as it increases sedimentation rates (Cunha et al. 2016); the additional sediment fills up reservoirs, and higher sediment loads in the rivers force water companies to turn off their pumps. Sedimentation can, therefore, impose a significant cost on citizens downstream, who will need to cope with lower water volumes or impaired water quality, especially in the dry seasons, with knock-on effects for their health and wellbeing and increased costs of water treatment (Keeler et al. 2012, Rozario et al. 2016).

The quantitative assessment of the impact of upstream forest loss on urban populations requires understanding of the location where the service is supplied, the spatial and temporal flows of the water ecosystem services, the demand and actual use of the services (or disservices) by beneficiaries, and features in the landscape that affect the flows (Bagstad et al. 2014, Villamagna et al. 2013). Timing, place, quantity and quality of water supply regulation are affected by landscape and ecosystem changes (Ponette-González et al. 2015), and are often felt off-site, but predicting hydrological responses to land-use change is challenging (Bagstad et al. 2014, Guswa et al. 2014, Villamagna et al. 2013). Integrated modelling provides an understanding of the link between natural woody habitats and water-related ecosystem services relevant to human wellbeing (Lele 2009). However, the lack of integrated approaches and over-simplification of hydrological processes is one of the main limiting factors for accurately valuing these services (Dennedy-Frank et al. 2016, Sharps et al. 2017). Existing ecosystem assessment tools such as Co$tingNature, ARIES and INVEST do not typically use local data or disaggregated land cover categories, are less applicable at smaller spatial scales, and often fail to account for seasonal variation in hydrological flows (Pandeya et al. 2016, Vigerstol and Aukema 2011).

Morever, forests and woodlands do not produce water *per se*, and so valuation of the total annual volume of water supplied has very limited policy relevance for understanding forest-related water services beneficial to people (Lele 2009). Valuing the cost or benefit of a *change* in a specific service provision throughout the year resulting from a *change* in forest quality or quantity is a more useful approach when aiming to value forest ecosystem services (Balmford et al. 2011, Daily et al. 2009).

Many previous studies, particularly in data-poor settings, have abstained from providing economic values for water-related services, or from linking economic values to changes in land use and subsequent forest functioning (Campbell and Tilley 2014, Maes et al. 2012, Terrado et al. 2014). Existing monetary valuation evidence is limited; for example, the TEEB (The Economics of Ecosystems and Biodiversity) valuation database (Van der Ploeg and De Groot 2010) provides only eight references and ten value estimates from primary studies for water-related benefits provided by tropical forests, of which none are from Africa. The value of landscape management for water related ecosystem services is hard to determine because of the lack of understanding of the dynamics of water ecosystems and interactions between land and water systems, and because the preferred quantity and quality depend on water users and time of year, and crucially; more water is not always better (Brauman 2015, Schaafsma et al. 2015).

The aim of this paper is to (a) assess to what extent the presence of forests and woodlands regulates the availability of water throughout the year in two major African cities, and (b) provide an estimate of the economic value of this regulation service. We tackled these aims by linking the outputs of the process-based model, the Soil and Water Assessment Tool (SWAT), to an economic valuation of the regulation service of woodland and forest ecosystems. Through a comparison of scenarios with and without tree-dominated ecosystems, we provide estimates of the monetary value of water regulation by forests and woodlands, and the distribution of benefits among different socio-economic groups. We demonstrate that our methodology is applicable to data scarce areas with a case study on the Ruvu catchment in Tanzania (Figure 1).

2. Case study area

World Bank urban development data show that the percentage of the population in Tanzania living in cities increased from 22% in 2000 to 31% in 2014. Dar es Salaam, with a population approaching 5 million (> 3000 persons per km^2 (Office of the Chief Government Statistician 2013), is expected to see a further 85% increase in population between 2010 and 2040. This will increase water demand in a city where the water companies already struggle to meet the water required by the existing population (Nganyanyuka et al. 2014, Reweta and Sampath 2000).

At the same time, the principal supplies of water to Dar es Salaam and Morogoro are at risk from upstream deforestation (Ngana et al. 2010, Nobert and Skinner 2016). Dar es Salaam city (the commercial capital and largest urban area in the country) and Morogoro town (the capital of Morogoro region) depend mainly on the Ruvu River for their surface water supply (Yanda and Munishi 2007). This river originates in the Uluguru Mountains, part of the Eastern Arc Mountains (Figure 1) – a mountain chain of global significance for its exceptional concentrations of rare and endemic plants and animals (Burgess et al. 2007, Rovero et al. 2014). Despite conservation efforts over many years, the conversion of forests to farmland has continued to the point where less than 30% of the original forest extent remains (Hall et al. 2009, Newmark 2002, Platts et al. 2011). The rate of forest loss has slowed in recent years, with almost no forest lost within reserves in the past decade. However, the frontier of forest conversion has reached the reserve boundaries, and woodlands – which are largely unprotected – continue to be rapidly converted to agriculture (Green et al. 2013). More subtle degradation of both protected and unprotected forests from illegal timber harvesting, charcoal production and firewood collection also continues to threaten biodiversity, carbon sequestration and hydrological services.

The Ruvu catchment covers an area of 14,390 km^2 and lies mainly in Morogoro Region, with small parts located in Pwani Region. Forest and woodland cover 35% of the catchment, while crops such as maize, African beans, rice, sesame, pineapple and sisal cover 10% (Swetnam et al. 2011). The remainder is mainly grassland and bushland. In the west of the catchment are the Uluguru Mountains, covering 3057 km^2, of which 309 km^2 is moist tropical forest (Platts et al. 2011). The soils in these mountains are mainly Luvisols with a sandy clay loam texture (Msanya et al. 2001), making them highly susceptible to erosion (Kimaro et al. 2008).

Three major rivers flow into the main Ruvu River: the Mgeta River flowing from the south-west of the catchment, the Upper Ruvu River flowing from the east side of the Uluguru Mountain, and the Ngerengere River flowing from the westside of the Uluguru Mountains. The main Ruvu River in this catchment is the principle source of fresh water to citizens of Dar es Salaam, and the Ngerengere River to citizens of Morogoro via the Mindu Dam. These two rivers, the Ruvu and Ngerengere, are the focus of this study.

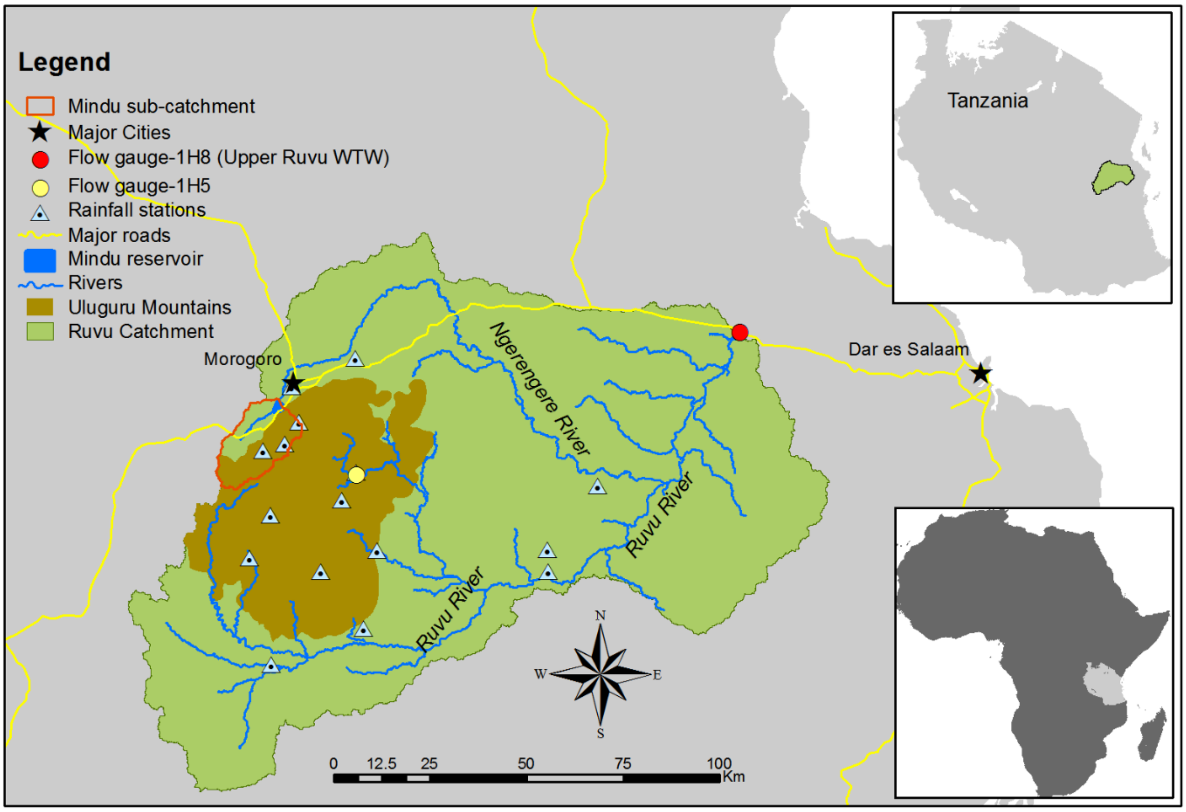

Figure 1: Ruvu catchment map with important features (rivers, reservoir, important towns)

In the 2000s it was estimated that 88% of the total water used in Dar es Salaam comes from the Ruvu River, with the other 12% coming from groundwater sources (Kjellén 2006). Piped water for Dar es Salaam came (and still comes) from three different water treatment works (WTW): Mtoni, Upper Ruvu, and Lower Ruvu. Our analysis focuses on the Upper Ruvu WTW located in Mlandizi, which receives its water only from the Ruvu River and is therefore fully and immediately dependent on the Uluguru Mountains area and its forest and woodland. The impact of deforestation on the Lower Ruvu WTW is not assessed in this study due to insufficient river flow data for model calibration and validation at the Lower Ruvu WTW water off-take point. Mtoni WTW is not assessed in this study, because its source location, the Kzinga river, lies outside the Ruvu catchment, and its contribution, 9,000 m^3/day, is much lower than the Upper Ruvu WTW with 80,000 m^3/day (Kjellén

2006). Our study uses landcover change information and these water distribution figures in the 2000s. The potential increase of water treatment costs due to erosion caused by upstream changes in land cover are beyond the scope of this study, as we do not have sufficient information to assess the treatment process, such as the use of polymers or alum used to remove suspended solids, or time series data of suspended solids (Cunha et al. 2016, Holmes 1988, Sthiannopkao et al. 2007, Spellman 2008, Vogl et al. 2017).

At the Morogoro Bridge, along the Dar es Salaam-Morogoro road (1H8, see Figure 1), water from the Ruvu River is pumped to the Upper Ruvu WTW and then conveyed to the Kimara reservoirs. The design treatment capacity of the Upper Ruvu WTW was 82,000 m^3/day (Kjellén 2006). However, the WTW was often unable to operate at full capacity, primarily because siltation of the Ruvu River caused pump failure, leading to regular water restrictions or rationing in Dar es Salaam (Gondwe 2000, Kjellén 2006). Past maintenance work commissioned to solve siltation problems was not successful (Gondwe 2000), including the Tanzanian Shillings (TZS) 300 million (USD 140 thousand) spent to replace existing pumps (Africa Time 2015)[1]. Moreover, water supply from the rivers was frequently insufficient. As a result, the Kimara reservoirs, with a total capacity of 34,200 m^3, were never full and often ran dry after the morning peak demand (Kjellén 2006). Illegal abstraction and leakage due to excess pressure within the distribution system were very common: of the total inflow at the pump, 47% was estimated to be either wasted, used illegally (primarily for agriculture) or lost at off-takes. In addition, an estimated 8% of the total inflow was leaked along the transmission line between the WTW and the reservoirs, and 14% fulfilled the legitimate demand for towns and villages along the transmission (Kjellén 2006). Only an estimated 32% of the potentially treated water, i.e. 26,240 m^3/day at full capacity, reached the service reservoir.

The Ngerengere River, which flows into the Ruvu River, supplies water to Morogoro via the Mindu Dam and reservoir. The Mindu Reservoir is located about 10 km south-west of Morogoro town. The main source of water to the Mindu Reservoir are the seasonal and perennial streams flowing from the forest and woodland reserve of the Uluguru Mountains situated at the eastern side of the reservoir (Ngonyani and Nkotagu 2007).

The Mindu reservoir supplies 80-85% of the water for Morogoro town, equivalent to 6,927,000 m^3/year, but this is only sufficient to meet 64% of the total water demand (MORUWSA 2009). The dam was constructed in 1983 (JICA 2013). However, within the last 30 years, the reservoir has lost 22% of its capacity due to siltation (AAW 2012). There have been no siltation removal operations since the dam was built (AAW 2012). Although the consultancy report (AAW 2012) also suggested various feasible dredging options, the Morogoro Urban Water and Sewerage Authority (MORUWASA) chose to raise the dam height by 2.5 m (MORUWASA 2017). Therefore, we analysed the cost of siltation based on the authority's strategy.

3. Methodology

3.1 Integrated Modelling and Scenarios

Forests and woodlands regulate the distribution of surface water across time and space and thus affect soil erosion. Estimating the water supply benefits of regulation of sedimentation by forests and woodlands is a multi-step process from land conversion together with weather patterns, to run-off and river sedimentation, distributed using man-made capital to the final beneficiaries, whose values differ. This complex process requires a scenario-based analysis to understand what would happen to urban water supply benefits if forest and woodland cover was lost to agriculture. Therefore, we modelled the response of Ruvu River flow in two extreme scenarios, representing the WTW conditions up to 2016. The first is a 'conversion' scenario, where due to uncontrolled

[1] In 2016 the water supply system for Dar es Salaam changed. See also the Discussion.

agricultural expansion all forests and woodlands in the Ruvu catchment are converted to cropland (maize and beans). The second is a ‘conservation’ scenario, where forest and woodland cover in the Ruvu catchment is assumed to remain at the same level as in the year 2000. By comparing the results of these scenarios, we quantified the role of woody habitats in the regulation of hydrological flow and sediment control, and their impact on domestic water supply to urban residents of Morogoro and Dar es Salaam.

As elsewhere in the Eastern Arc Mountains, woodlands in the Ruvu catchment are largely unprotected, and the majority forests outside reserve boundaries have already been cleared (Green et al. 2013). Our conversion scenario represents a case where funding is withdrawn, and conversion continues into the Uluguru Nature Reserve, which contains most of the forest in the catchment (Burgess et al. 2002), until all forests and woodlands are lost from the Ruvu catchment. In contrast, the conservation scenario reflects that management of the Uluguru Nature Reserve is effective in stopping conversion, and assumes similar levels of protection are extended to the woodlands.

We used SWAT to examine how changes in sedimentation affect the capacity of the Mindu Reservoir and the functioning of the pumps supplying Dar es Salaam (see Section 3.2). For the assessment of economic consequences in Dar es Salaam and Morogoro, we related sedimentation levels to the resulting water supply problems (see Section 3.5).

3.2 Hydrological model

In this study, we chose to use the SWAT model to simulate the Mindu reservoir water level and its sediment deposition, and the operations of the pumps that deliver water from the Ruvu River to the Upper Ruvu WTW. We chose the SWAT model because of it flexibility, longevity and – crucially - its capability to model sediment rates at daily time steps, which is necessary to assess the pump shutdown events that depend on short-term sediment levels (rather than longer-term average water quality indicators). SWAT is a freely available physical process-based model that can simulate continuous-time catchment scale processes (Neitsch et al. 2011). Once the model is setup, different management strategies and changes such as land use/cover can be assessed easily without excessive investment of time and resources (Ashagre 2009, Baker and Miller 2013). Since the model is integrated with a GIS interface it is convenient to analyse and present spatial variations (Easton et al. 2010).

SWAT addresses various water-related processes at watershed scale (Francesconi et al. 2016). It can be used to identify runoff sources, areas of high soil loss, and the downstream consequences of the land cover change. Its application has been successful at various temporal and spatial scales, in data-scarce catchments, in both temperate and sub-tropical catchments. Although the model can be data demanding, it has been used in data scarce areas with satisfactory accuracy (Betrie et al. 2011, Ndomba et al. 2008, Nyeko 2015). Several studies have used SWAT to quantify provisioning and regulating services, but very few peer-reviewed publications have used SWAT for valuing ecosystem services (Francesconi et al. 2016), let alone in a Sub-Saharan context (Vogl et al. 2017). SWAT has been applied in Tanzania to assess the impact of land management practices and land cover changes on the watershed water balance (Ashagre et al. 2014, Dessu and Melesse 2013, Mango et al. 2011, Natkhin et al. 2015, Ndomba et al. 2008, Notter et al. 2012, van Griensven et al. 2013, Wambura et al. 2015), but never in combination with valuation.

Applying a process-based hydrological modelling tool, such as SWAT, in data-scarce catchments is a challenge (Baker and Miller 2013, Dile and Srinivasan 2014, Ndomba et al. 2008, Nyeko 2015), mainly due to the need for detailed model parameters and input variables such as rainfall, solar radiation, plant growth, leaf area index, local soils, representative soil profiles, hydraulic properties of soils, soil erodibility factors, land-use, irrigation management, crop management, and water abstraction. Because of the non-linear nature of hydrological processes and the uncertainties in measured parameters, it is important to evaluate model performance against measured data, commonly done by using river flow and sediment load in rivers. However, these data are scarce in catchments like the Ruvu, and due to infrequent maintenance of the few guaging stations, the measured data can show significant error. In this study, we used various techniques to fill gaps and reduce uncertainty in measured data. For example, we used literature to develop a crop database for plants that are not listed in the original SWAT database (See Appendix 1, Table A1.3), and we adapted the SWAT model to account for leaf shed in the dry season of forests and woodlands in the catchment. This leaf fall contributes to the nutrient pool and allows for forest growth (see Appendix 2). We incorporated these modifications into a freely available version of the SWAT model (http://swat.tamu.edu/).

In the model development, we assimilated rainfall data from 19 stations but only data from 16 stations were suitable for use in setting up the model. Out of the 16 stations only seven have reliable data for the period 1995 – 2004, with some gaps. The rainfall datasets from the other nine stations either have no data for the period 1995 – 2004 or have several days of missing data points. Most climate stations fell apart in the early 1990s after the economy collapse in 1980 and have not been restored since. We filled these data gaps using the WXGEN weather generator model (Williams and Singh 1995) by using the strong historical dataset before 1995 (see Appendix 1 – rainfall data). We adopted the land cover map from Swetnam et al. (2011) which is based on a 2000 land cover map with some updates. For soils, we georeferenced the map of Hathout (1983) (see Appendix 1, Figures A1.1 and A1.2), which identifies 16 major soil types in the catchment, based on texture and the number of soil layers. We took representative soil profiles, for each soil type, from (Kimaro et al. 2001, Mbogoni et al. 2005, Msanya et al. 2001, Spooner and Jenkin 1966). Other data included soil depth and other soil hydrological properties, agricultural management practices and water extraction – for further details, see Ashagre (2009) and Easton et al. (2010).

The SWAT model uses the Modified Universal Soil Loss Equation (MUSLE) to calculate daily surface soil erosion and sediment concentration in the streams (Neitsch et al. 2011). Due to the scarcity of data on sediment concentration or total suspended load, we used turbidity as a proxy measure in this study. Based on correlation estimates from Grayson et al. (1996) for a comparable catchment, we estimated the suspended soil to be a factor 0.9 of turbidity for values lower than 1000 NTU (Nephelometric Turbidity Units); for turbidity values higher than 1000 NTU, total suspended solid is about 2.7 times the turbidity.

3.3 SWAT calibration and validation

We calibrated SWAT using daily rainfall data from the 16 weather stations spanning the years 1995 – 2000 with a model warming-up period of five years, 1990 - 1995. We calibrated the model for flow estimation mainly using flow data from two points: Kibungo (gauge 1H5) and Morogoro Bridge (1H8, see Figure 1). The intake point at Morogoro Road Bridge (1H8) is the outlet of the Ruvu catchment in this study. It was not possible to use statistical tests to assess model performance at the catchment outlet, 1H8, due to insufficient data points within the calibration and validation period. Instead, we used the flow point at 1H5, which is a sub-basin outlet on the Uluguru Mountains, to test the model accuracy during the calibration process using three goodness-of-fit recommended by Moriasi et al. (2007): the model R^2, the percentage bias (PBIAS) of -11.8% and the Nash-Sutcliffe Coefficient (NSE). The NSE has a value of 1 for perfect model fit, 0-1 when the model is better than taking an average value, and <0 for very low model fit (Coffey et al. 2004). We transferred the calibrated parameters over the whole catchment and used the available data at 1H8 to fine-tune the model by using a visual/graphical approach. Although parameter transfer can reduce model performance, previous applications of SWAT have shown that transferring parameter values within the catchment performs reasonably well (Heuvelmans et al. 2004, Huisman et al. 2003). We validated the model using flow data at 1H5 for the period of four years, 2001-2004, the details of which we discuss in the Results section.

We further calibrated the SWAT model for sediment concentration in the streams by comparing the modelled river sediment concentration to the sediment concentration estimated using the turbidity data at 1H8 from Lopa et al. (2012). Additionally, we calibrated the model for sediment load and reservoir volume at the Mindu dam, using information on dam capacity, operation and loss of capacity due to siltation. We could not validate the model for its accuracy in simulating sediment concentration in the Ruvu River, because daily sediment data or turbidity data for the validation period were unavailable.

3.4 Scenario analysis

Both scenarios assume the same rainfall and climatic conditions that are measured and used for the model calibration period, 1995 – 2000. Comparing the scenario results thus indicates how flow and sediment concentrations would be altered if the forests and woodlands in the Ruvu catchment were replaced with the two most dominant crops: maize and beans (Green et al. 2013). We ran the two scenarios at a catchment scale and analysed them at catchment and sub-basin scale where the Mindu Reservoir is located.

For Morogoro, in the absence of measured records of the outflow from the Mindu reservoir, we estimated the outflow in the SWAT model by using a storage target: the principal volume of the reservoir. We simplified the spill control from the dam reservoir and assumed that any water coming into the reservoir above this volume overflows to downstream areas (this has no material impact on our results). No measures are taken in the scenarios to reduce sedimentation in the Mindu reservoir, so that soil erosion-induced sedimentation results in the reduction of reservoir capacity.

For Dar es Salaam, we based the analysis of the value of water-regulation services provided by forests and woodlands of the Ruvu catchment on the incidence of pump failure due to sedimentation at the Upper Ruvu WTW offtake point at Morogoro Bridge (1H8) in the two scenarios. It has been reported on several occasions that the Upper Ruvu WTW offtake-pumps, located at Morogoro Bridge (1H8), have stopped operating due to the high concentration of sediment in the river. The Dar es Salaam Water and Sewerage Corporation (DAWASCO) were said to switch off their pumps at NTU values above 1500, sometimes multiple times per day (M. Cadman, pers. comm.), but we could not corroborate this information with DAWASCO documentation. This NTU level is well above safety standards for drinking water quality (<5 NTU) and turbidity levels that can cause pump problems >10NTU (Uhrich and Bragg 2003). Data on the number of days and hours that the pumps have been turned off due to sediment problems were unavailable. Therefore, we used the slope of the exceedance curve of the conversion scenario to determine the minimum sediment concentration in the river that causes pump failure or deliberate cut-off to protect pumps from failure (see Appendix 3). The range of interest is below this maximum percentage, where the exceedance curve is gradual and sediment concentrations are high. For this range, where a major increase in sediment concentration leads to a small increase in the probability of sediment exceedance, we estimated the frequency and costs of pump cut-off under both scenarios.

3.5 Monetary valuation

A range of valuation methods is available for valuing (urban) ecosystem services, and avoided expenditure and replacement cost methods are most often used for regulation services (Gómez-Baggethun et al. 2013). We adopted cost-based approaches to value the changes in water supply to Morogoro and Dar es Salaam. Benefit transfer was impossible, because relevant studies on the monetary value for water-related benefits provided by tropical forests were unavailable. Specific studies or data for Tanzania on the costs of damages to approximate the value of supply changes, such as health problems or time lost to increased water collection time were unavailable. The budget of the study was too limited to collect primary data with methods requiring large samples.

We therefore adopted a cost-based valuation approach to relate the annual sedimentation of the Mindu reservoir to the (avoided) costs of increasing the Mindu Dam height to maintain the reservoir capacity, and thereby the water supply to Morogoro, using information from a recent consultancy report on the dam (AAW 2012).

For the valuation of impacts on the water supply to Dar as Salaam, we used market pricing and substitute cost methods and developed a set of rule-based assumptions based on existing studies of the water market in the city, as presented in Section 4.4. The main price information for substitute water sources was obtained from secondary data: public websites, the DAWASCO website, and published reports (see Table A3.3). In a small survey, we collected additional primary data on substitute costs in three districts of Dar es Salaam in April 2015 (see Appendix 4). We interviewed 36 kiosks, 22 pushcart vendors, and six trucks to obtain price information for different water sources, during dry and wet seasons, and during water rationed and non-rationed periods.

4. Results and discussion

4.1 Model Accuracy

The SWAT model achieved good agreement between measured (dark blue) and simulated (light blue) river flows at 1H5 and 1H8, except for over-estimation of the base flow in some years (Figure 2ab). The model accuracy in the calibration process, simulating flow at 1H5 as compared to the measured flow, had a coefficient of determination (R^2) of 0.45, an NSE of 0.25, and a PBIAS of -11.8%.

We used the estimated sediment concentration from measured turbidity data (panel c in Figure 2), which exhibited considerable uncertainty, to guide the sediment calibration process. When the measured data exhibit significant uncertainty, calibration of models using goodness-to-fit measures can misinform the modeller. Hence, we use the sediment data derived from turbidity data only for guidance purposes. With the current parameters set, comparing model outputs with measured data (turbidity) showed that the model did not overestimate the sediment concentration in the river, suggesting that our estimates of soil loss were conservative, and the model fit for purpose. The calibrated model showed that highest soil erosion occurs in November to January (see Figure 2c). Sediment load is high from September to December, even though rainfall is highest in March and April, probably because the higher vegetation cover in the March to May period reduces surface runoff and subsequent soil erosion. Later in the year (September to December), following the long dry season (June to September/October), the ground is bare and moderate rainfall can cause significant erosion, especially in areas that are burnt in preparation for the planting season (Heckmann 2014, Itani 1998, Kato 2001).

During the calibration period, in terms of stream flow simulation, the model slightly but consistently overestimated the flow rate during the dry season, which resulted in a low NSE value and a negative PBIAS. The R^2 was high showing a good collinearity between the simulated and the measured data. Based on suggested model performance grade by Moriasi et al. (2007), the model performed almost satisfactory according to the R^2 and NSE, and satisfactory based on the PBIAS. The model did neither overestimate flow nor sediment. The conservative model results during the high flow season are important for the use of sediment concentration outcomes as the determining factor for pump shutdown at the WTW.

The model validation, run for the period 2001 – 2004, resulted in a similar model accuracy to that of the calibration period although 2003 has a different rainfall pattern than the other years. During validation, the model's goodness-of-fit measures are: an R^2 value of 0.40, an NSE coefficient of 0.20, and a PBIAS of -20.3%. The model showed a slight delay in flow in post-rain season periods, which is mainly due to slower recession in ground water flow and lateral flow in the model, which is also observed during the calibration period. The simulated flow showed a good correlation with the lower flows and the high flow events (see Figure 2d), and we hence deemed the model performance in simulating the surface runoff sufficient to perform further analysis.

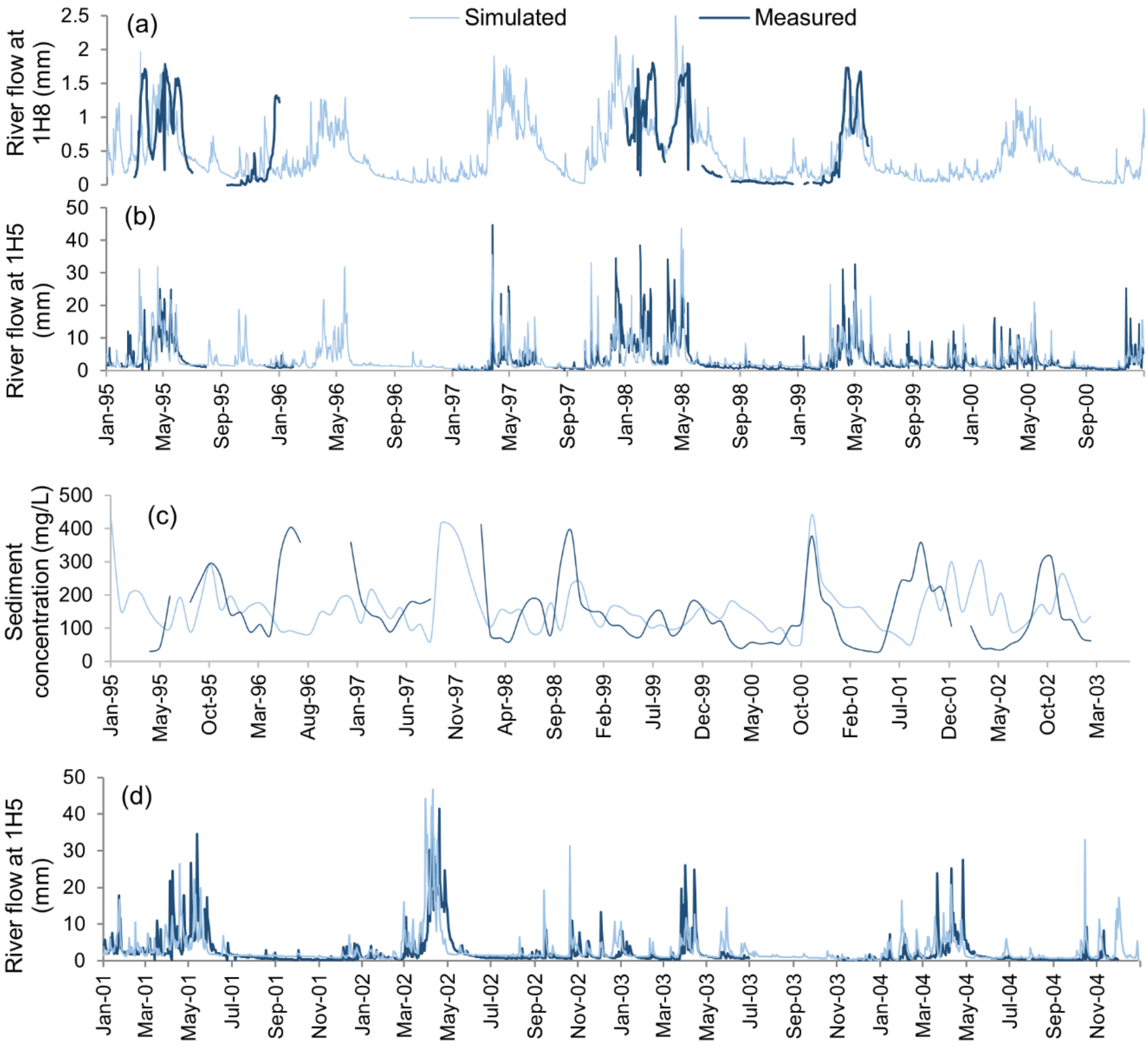

Figure 2: a) Daily measured (dark blue lines) and simulated (light blue lines) flow of Ruvu River at Morogoro Bridge during calibration (1H8); b) Daily measured and simulated flow of Ruvu River at Kibungu (1H5) during calibration; c) Monthly average simulated sediment concentration and the sediment concetration estimated based on measured turbidity data at the outlet of the Ruvu sub-basin during calibration (1H8); d) Daily measured and simulated flow of Ruvu River at Kibungu (1H5) during validation;

4.2 Sediment source areas under the conservation and conversion scenarios

In the conservation scenario, we estimate the mean annual rate of soil loss in the Mindu Catchment to be 4.43 tonnes/ha, but this rate varies across the catchment (Figure 3ab). The main sources of erosion are where agriculture (mainly maize and other annual crops) on steep slopes on the Uluguru Mountains (Figure 3a). Agricultural lands on shallower slopes do not show significant soil loss.

Under the conversion scenario, the highest sediment yields are generated from forest and woodland areas that are cleared for agriculture (Figure 3b), particularly in the mountains, where steeply sloping land and Luvisol soils have high potential for soil erosion. The mean annual rate of soil loss more than doubles, compared to the conservation scenario, to 10.50 tonnes/ha. The additional sediment from erosion due to land cover change totals 187,000 tonnes/yr across the 30,800 ha upstream catchment of Mindu Reservoir.

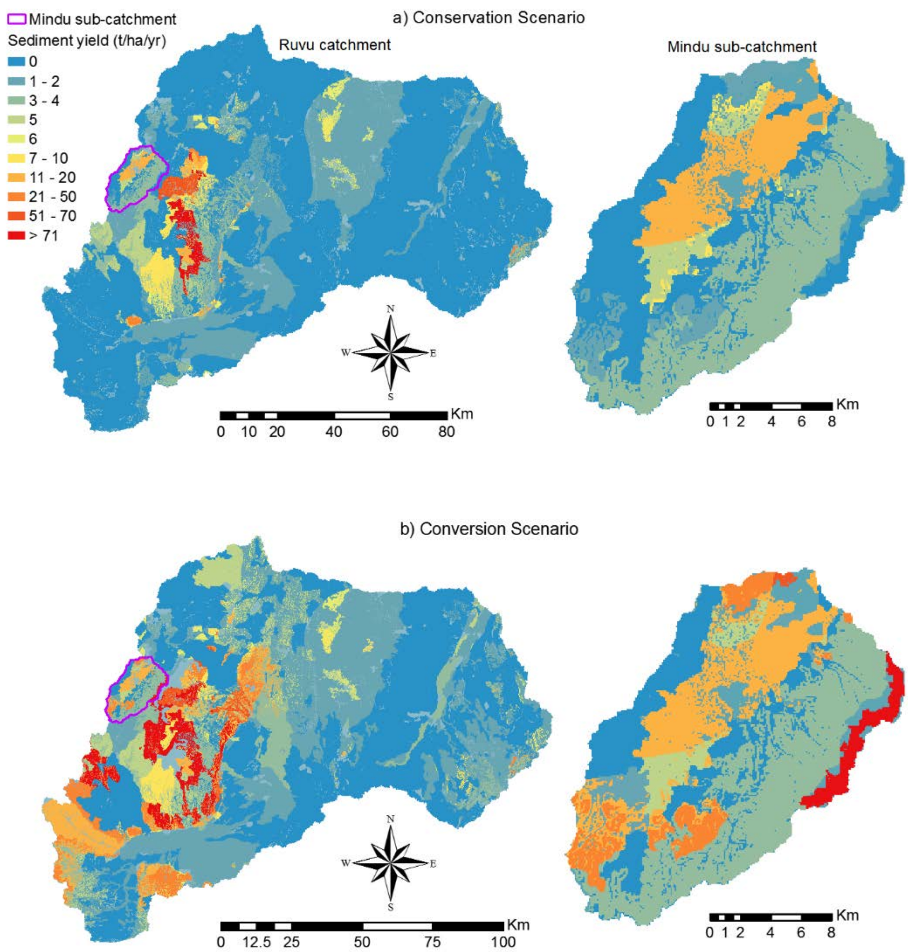

Figure 3: Comparison of rates and patterns of soil erosion under our conservation and conversion scenarios; a) soil erosion in Ruvu Catchment and Mindu Sub-catchment under the conservation scenario; b) soil erosion in Ruvu Catchment and Mindu sub-catchment under the conversion scenario.

4.3 Mindu reservoir siltation and costs of water supply to Morogoro

Annual sedimentation is estimated at 0.157 million m^3/year and has reduced the capacity from 20.7 million m^3 at design to 16.0 million m^3 by 2012 (AAW 2012). Assuming all surface erosion from the Mindu catchment enters the Mindu Reservoir (i.e. with no sediment deposition in streams and depressions within the catchment), we estimated that on average the reservoir volume lost per year increases from 0.156 million m^3 (1% of reservoir volume) in the conservation scenario to 0.280 million m^3 (1.75% of reservoir volume) in the conversion scenario. If no action is taken to remove siltation, based on the conversion siltation rate, it would take 57 years to fill up the reservoir instead of 102 years based on the conservation scenario.

MOROWASA estimated that increasing the dam height and constructing upstream check dams to regain the design capacity (AAW 2012), i.e. the volume of water storage, would cost TZS 14 billion (~ USD 6.55 million) (MOROWASA water engineer, pers. comm., September 2015). Based on this figure, we estimated the cost of siltation at TZS 496 million per year (~USD 218,273) in the conservation scenario, equivalent to an annual cost of TZS 3750/tonne (USD 1.65/tonne) of sediment (see Appendix 4 for details). The conversion of forests and woodlands to cropland would result in an additional cost of TZS 700 million per year (~USD 308,103).

4.4 Water supply to Dar es Salaam

Using the SWAT results on sedimentation levels, combined with rules on the maximum sedimentation that the pumps can deal with, we defined the number of days that the pumps were not functional due to high turbidity (see 4.4.1). Next, we estimated the number of downstream people affected by pump failure at the Upper Ruvu offtake point (see 4.4.2). We related pump failure to substitution behaviour (i.e. people switching to alternatives for tap water), and estimated the costs of these substitution options using water price data (see 4.4.3). Finally, we estimated the increase in water costs incurred because of upstream loss of woody landcover (see 4.4.4).

4.4.1 Pump failure at Upper Ruvu offtake point

Figure 4 shows that the modelled sediment concentration at Morogoro Bridge (1H8) in the conversion scenario is, on average, 340% higher than in the conservation scenario.

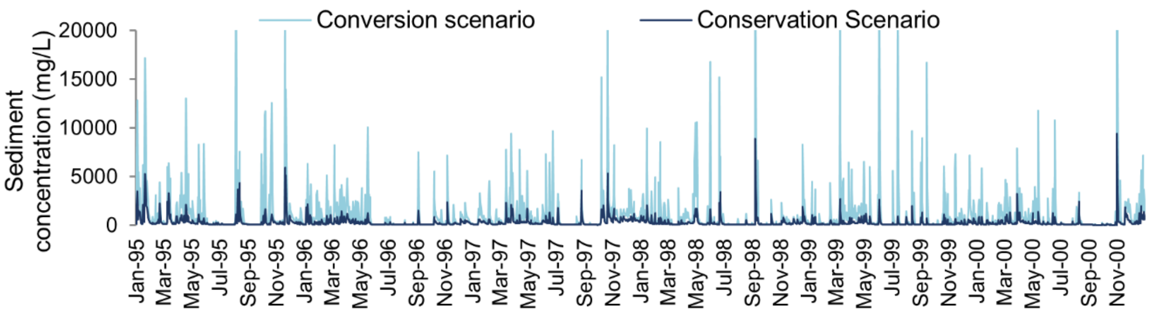

Figure 4: Sediment concentration at Morogoro Bridge (1H8) in conservation and conversion scenarios.

Using the exceedance curves, we estimated the number of days that pumps are turned off due to high sediment concentrations for 0.25% to 2.0% of the year, one to seven days a year respectively. The choice of this range is described in more detail in Appendix 3. Combined with the SWAT sediment estimates for the conservation scenario, this range suggested that the pumps are turned off at sediment concentrations of 1885-4357 mg/L (Table 1 and Appendix 3, Table A3.1 and Figure A3.2). The minimum sediment concentration level to cause pump cut-off (1885 mg/L resulting in seven days of pump cut-off per year) is above the suggested operational pumping cut-off level of 1500 NTU. The SWAT sediment estimates for the conversion scenario in turn suggest that conversion of the Ruvu catchment's forests and woodlands would cause tap water to be unavailable in Dar es Salaam on 20 to 51 days each year (depending on the exact cut-off level, see final column of Table 1). Our results suggest that pump failure due to high sedimentation in the Ruvu River would not only lead to more frequent but also longer periods of pump outage in Dar es Salaam (see Appendix 4, Table A4.1 versus A4.2).

Table 1. Number of days of that pumps are stopped under conservation and conversion scenario for different assumptions of cut-off sedimentation concentration levels.

Percentage of time pumps stopped due to sediment (Conservation)	Number of days per year pumps are stopped (Conservation)	Cut off sediment concentration mg/L (NTU)	Percentage of time pumps stopped (Conversion)	Number of days per year pumps stopped (Conversion)
0.25%	0.9	4357 (1614)	5.45%	19.9
0.50%	1.8	3495 (1294)	6.85%	25.0
0.75%	2.7	2812 (1041)	8.70%	31.8
1.00%	3.7	2491 (923)	10.05%	36.7
1.25%	4.6	2282 (845)	11.40%	41.6
1.50%	5.5	2106 (780)	12.20%	44.5
1.75%	6.4	2029 (751)	12.90%	47.1
2.00%	7.3	1885 (698)	13.89%	50.7

4.4.2 Number of water consumers affected

Rates of household access to safe water sources in Dar es Salaam cannot be determined with certainty (Bayliss and Tukai 2011); hence the volume of tap water used by households is unknown. About 60% of the total demand for water in Dar es Salaam is domestic, 10% commercial, 10% industrial and 20% institutional (WaterAid-Tanzania and Tearfund 2003). Although commercial, industrial, and institutional demand is more likely to be fulfilled by tap water compared to domestic use, we assumed that these percentages hold true for allocation of Upper Ruvu water. Hence, we assumed that 60% of the 26,240 m^3/day that reaches the Kimara service reservoirs from Upper Ruvu (Kjellén 2006), i.e. 15,744 m^3/day (15.7 million litres), is available for domestic use (see Table 2). This assumption may overestimate the available water for domestic use as it ignores further leakage from the distribution system (*ibid.*). Households that are supplied by the Upper Ruvu WTW are not provided with tap water from other sources in the water distribution network, for example, from the Lower Ruvu WTW (Bayliss and Tukai 2011). We hence assumed that stopping pumps results in an immediate stop in the supply of piped water to the Upper Ruvu supply area. The storage capacity reported by DAWASCO in 2012/13 was much lower than the demand, with a storage capacity duration of just 3.4 hours; an Energy and Water Utilities Regulatory Authority report (EWURA 2013) shows that there was hardly any buffer at all, which justified this assumption.

DAWASCO estimated that the average per capita consumption is 40 litres per day, which is expected to apply to connected households (EWURA 2013). Tanzania's National Water Policy (2002) objective is to ensure the provision of 25 litres of potable water per capita per day. Ease of access tends to lead to higher per capita use of water among households with their own taps, compared with other households. These figures are lower than of the total water use per household in Rostapshova et al. (2014). The difference in water consumption lies mainly in drinking water use; for cooking, washing, and cleaning non-piped sources are more prevalent among those without taps at home (Rostapshova et al. 2014). We used these volumes per capita to estimate the number of households that receive water from the Upper Ruvu: 40 litres for households with easy access via a tap, and 25 litres of piped water per day for other households, who buy DAWASCO water from their neighbours, kiosks or vendors. We assumed that households use non-piped water to fulfil further non-drinking water demand based on (Bayliss and Tukai 2011).

Around 62% of people in Dar es Salaam get their water from a tap (National Bureau of Statistics 2009), but only 8% have a tap at home. Others get piped water through neighbours (38%), or kiosks or vendors (16%). These groups also tend to vary in wealth and substitution behaviour. Therefore, we disaggregated the benefits of water supply by these groups in subsequent steps.

From these figures, we allocated the total volume provided by the Upper Ruvu to the different user groups, and estimated the number of people within each user group (Table 2). We inferred that an estimated 584,508 people depend on Upper Ruvu water. Their domestic water consumption is affected each day that the pumps are shut down due to excessive sedimentation.

Table 2. Piped water use from Upper Ruvu, volume (in litres) and number of users per water source

Source	% population (NBS 2009)	Piped water use (L/capita/day)	Upper Ruvu Supply (1000 L/day)	# people (Ruvu-users)
Tap at home	8%	40	3,017	75,420
Tap from neighbours	38%	25	8,956	358,247
Kiosk, vendor	16%	25	3,771	150,841
Non-piped water	38%	0	0	0
Total	*100%*		*15,744*	*584,508*

4.4.3 Substitution options and costs

Because of frequent rationing of water in Dar es Salaam, households use multiple sources of water. Alternative sources include groundwater, rainwater, surface water (streams, rivers) and water from other areas brought in by water trucks. Access to one's own tap water is skewed towards the richer population: only 3% of the poorest quintile are connected to a public network tap compared to 24% of the wealthiest quintile, and 18% of the poorest quintile obtain drinking water mainly from vendors (Rostapshova et al. 2014). Different groups opt for different substitutes. Water vendors are the most used alternative (Nganyanyuka et al. 2014, Thompson et al. 2000), but richer households sometimes buy in bulk from tanker trucks or use privately owned tanks or reservoirs (Bayliss and Tukai 2011). Based on this information, we developed a set of rules for water substitution to pushcarts, trucks or bottled water, depending on the source of piped water and the number of consecutive days of pump failure (see Table A4.3). For households with taps at home, we assumed that they would reduce their usage to 30 litres if water rationing lasted three or more days, but for other groups we assumed that they would not cut back the volume used based on Rostapshova et al. (2014) and Bayliss and Tukai (2011).

According to our primary data, prices of these substitute water sources vary across vendors, water sources and between rationed and non-rationed days (see Table A4.4). The primary data and existing data from Kjellén (2006), DAWASCO (2013), and Mwakalila (2007) show that piped tap water is cheapest. Water prices at kiosks, although officially set at TZS 20 per 20 litres (~USD 0.01), increase significantly when tap water is cut off or rationed (Uwasi 2010).

4.4.4 Net costs of removing forest and woodland

We used the price variation and substitution behaviour information to estimate the increase in water costs incurred because of upstream loss of woody land covers. The estimated costs associated with a normal, non-rationed day for people depending on the Upper Ruvu WTW for their piped water are approximately TZS 90 million per day (USD 42 thousand), equivalent to ~ TZS 154 per person per day (USD 0.07) in 2015 prices (see Table 3). Our survey data showed that an increase in prices, especially for those households who normally depend on the relatively cheap taps of neighbours, occurs when pumps fail. If pumps also fail the next day, costs of richer households depending on piped water at home would increase, as we assumed that their buffer would be depleted and they would buy expensive, high-quality alternatives. On the third and each consecutive day, another sharp daily price increase is expected for those who depend on neighbours' taps. The richest households would be able to reduce their costs compared to the second day because they would arrange water truck deliveries.

Table 3. Costs per user group of piped water for normal and pump failure days (in millions of TZS/day for first four rows)

Source	normal day	1st day failure	2nd day failure	3rd+ day failure
Tap at home	3	9	266	232
Tap from neighbours	29	214	231	1,073
Kiosk, pushcart vendor	59	90	90	90
Total	*90*	*306*	*587*	*1,395*
Mean cost person/day (TZS)	154	524	1004	2386

From this, we estimate that the annual costs associated with increased pump failure under the conversion scenario compared with the conservation scenario vary from TZS 9.8 billion (using a cut-off level of 4357 mg/L from Table 1) to TZS 37.5 billion (for a cut-off of 1885 mg/L; Table 4 and full details in Table A4.5), equivalent to USD 4.6-17.6 million per year. Per capita estimates of these losses vary from TZS 16,824 up to TZS 64,241 per year (USD 7.87-30.05).

Table 4. Annual cost of cut-off events resulting from increased sedimentation in Upper Ruvu (conversion minus conservation scenario) (in millions of TZS)

Cut-off levels	4357 mg/L	3495 mg/L	2812 mg/L	2491 mg/L	2282 mg/L	2106 mg/L	2029 mg/L	1885 mg/L
Total cost (in million TZS)	9,834	12,891	19,062	23,344	27,879	31,216	32,667	37,550
Mean per capita costs (in TZS)	16,824	22,054	32,612	39,939	47,696	53,405	55,887	64,241

4.5 Discussion

While the importance of sustainable management of hydrological services and its relation to poverty alleviation, food security, habitat management, and urbanisation are well recognised worldwide, their accurate assessment is challenging, especially in the tropics. The analysis of this paper focuses on the delivery of potable water to households via the Upper Ruvu pump system to the population of Dar es Salaam and via the Mindu Reservoir to the urban dwellers of Morogoro. The results of the integrated modelling exercise presented here suggest that maintaining the forests and woodlands in the Ruvu catchment, and particularly in the Uluguru Mountains, is important for water provision in downstream cities, and the costs of converting to agriculture is substantial. Forest and woodland conservation would avoid between 20 to 51 days per year of water supply limitations to Dar es Salaam and thereby substitution costs to users, as well as considerable dam investments costs for Morogoro.

We see as the main contribution to the literature our integrated modelling approach applied in a data scarce area using a scenario-based approach to estimate the effect of forest cover change to downstream domestic water supply. Integrated catchment studies are essential to deal with the interlinked challenges of water provision, especially in countries that happen to be data-poor. Our paper demonstrates a possible approach, but considerable uncertainties and challenges remain, as we outline below.

First of all, in 2016 the water supply system for Dar es Salaam changed and new, larger pumps were installed, but we could not incorporate this in the modelling because there are no comparable data from the 2010-2016 period to enable this modification. Without any public information on the sensitivity of the new pumps to sediment rates, we cannot tell whether our quantified outcomes for Dar es Salaam still hold, but the qualitative findings would be expected to remain relevant and it does not require altering our methodological approach. The modification of the system has no effect on the value of water provision to Morogoro.

While we needed a tool like SWAT that can relate changes in land-use to downstream changes in water quality and quantity at a fine spatial and temporal scale, such tools are often data demanding. Due to data scarcity, of which most pressing are data for the hydrological model setup and calibration, pump management in response to sedimentation, and substitution behaviour of tap water users our methodological approach relied on a series of assumptions based on available statistics and other evidence. We considered the SWAT model estimates of the suspended sediment concentration sufficiently robust to use the outputs for value assessment. The model accuracy in the simulation of sediment concentration and yield can be improved by monitoring sediment concentration for an extended period, and estimation of a turbidity-to-sediment-concentration-curve (Fisher et al. 2017). A recommendation following from our study would be to invest in data monitoring. The SWAT model consistently over-estimated soil erosion for the month of January, potentially because of the minimum assumed uniform USLE management factor, a model parameter for soil conservation due to different practices or crop cover (Wischmeier 1979). Our estimated mean soil loss rate in the Mindu Catchment of 4.43 tonnes/ha/yr on average is lower than the average figure estimated in AAW (2012) of 6.5 tonnes/ha/yr. The lower soil loss estimation in the model is mainly because our analysis only covers soil loss from surface erosion and excludes other types of erosion, such as gully erosion, for which data were unavailable (Ashagre 2009). This means that our ecosystem service estimates are probably conservative.

In addition, we did not consider climate change projections in the scenario analysis. Conway et al. (2017) studied future climate and trends using 34 general circulation models. Two-thirds of these models indicated more frequent extreme rainfall events in Tanzania, i.e. higher likelihood of intense rainfall and prolonged dry spells. In addition, the model ensemble rainfall predictions by GLOWS-FIU (2014) suggested that the existing seasonality in the Ruvu catchment will be preserved under future climate scenarios with an increase in rainfall during March and April. Higher intensity rainfall is usually associated with higher soil erosion and flooding (Arnaud et al. 2002, De Risi et al. 2018, Römkens et al. 2002). Therefore, the impact of removing woody habitats from upstream catchments could result in higher rates of soil loss and peak discharges than reported here. Similarly, the level of water scarcity in this study could be under-estimated (climate projects suggests longer dry spells). Hence, our conclusions regarding the value of forests and woodlands for water-related services would likely be reinforced by considering future climate change scenarios.

Another challenge relates to linking hydrological models and economic valuation. We demonstrate that to understand how forest and woodland cover changes affect the benefits of water-related services, a comparison of two situations or scenarios with different land-use patterns and therefore water quantity and quality is a useful and feasible approach. Data availability and budget limitations meant that only a limited set of valuation methods was possible. Our estimates are probably cautious because we did not assess the non-financial health costs of reduced water use or substitution. Water consumers, especially poorer households who cannot afford to buy an equal amount of water when prices increase under water shortages, may either have to resort to other sources, often of lower quality, or buy less water; Bayliss and Tukai (2011) found that they opt to spend more as they cannot cut down further. We did not include the costs of obtaining substitutes, such as longer walking distances, or the health costs or using less or low-quality water, e.g. Collier et al. (2012), Dupont and Jahan (2012), Zivin et al. (2011). In many of the informal settlements in Dar es Salaam, piped water infrastructure is not available and these areas rely to a great extent on groundwater resources (Bayliss and Tukai 2011). However, the groundwater table is decreasing, and salinity due to increased industrial expansion and uncontrolled drilling is already a problem in several areas (Meena and Sharif 2008, Mtoni et al. 2012, Van Camp et al. 2014). Due to salinization, in combination with pit latrine contamination, the quality of both groundwater and vendor water is not of safe standards (Kalugendo 2008). Our water valuation methodology ignores price elasticity effects on water demand, but available elasticity estimates for other developing countries tend to show that demand for domestic water demand, and especially for potable water, is inelastic, albeit not perfectly (Nauges and Whittington 2010, Noll et al. 2000). However, any upward bias in our value estimates from ignoring price elasticity of demand is expected to be offset by the substitution cost components that we excluded. Furthermore, we did not include the impacts of changing water flows on illegal users of Upper Ruvu water, water losses in the distribution system, impacts on commercial, public and industrial sectors, and impacts on water use outside the urban areas, including hydropower and irrigation. Costs associated with river water quality deterioration resulting from deforestation were beyond the scope of this paper. Finally, impacts of deforestation on riverine flooding in these cities have not been assessed, but they are known to occur and lead to casualties, emergency displacements, and serious public health problems (De Risi et al. 2018, IFRC 2011).

Whilst our analysis supports forest and woodland conservation arguments, the opportunity costs of conservation include agricultural yields foregone and any one-off revenues from clearing forest cover, as well as the management costs of forest protection (Green et al. 2012). Importantly, this trade-off involves vulnerable people in urban and rural areas: conservation may help to deliver safe water to urban dwellers downstream, but may limit food security of the rural population upstream (Fisher et al. 2011). One option to address this trade-off would be to set up a payments for ecosystem/watershed services scheme, where urban beneficiaries, or the intermediate water supply companies, pay rural populations for improved forest maintenance. Existing pilots of such schemes in Tanzania provide mixed results: after two pilots in the Uluguru Mountains (Lopa et al. 2012), the attempts have lapsed, but the two pilot periods in the East Usambara Mountains have resulted in some continuation of payments from the Tanga water company to upstream stakeholders (Kaczan et al. 2011).

5. Conclusion

Dar es Salaam's population is rapidly increasing. This urbanisation process will further exacerbate the already stressed water situation in the city. Population growth combined with an expected increase in the number of middle-income households will increase demand for piped water, which will put even more pressure on the Government's obligation to provide potable water. Our analysis has demonstrated that the poorest households are most affected by failure to provide reliable tap water. Richer families not only enjoy the cheaper piped water, but they also have access to less expensive substitutes in case of short water supply failure. The poorest families are unlikely to be able to absorb the price hikes that occur when water is rationed, which would account for a considerable portion of annual income (Smiley 2013). They may therefore be forced to use lower quality water sources or less water.

Our study shows that sustainable management of catchment forests and woodlands, especially in the mountains, is crucial for the health and wellbeing of people living downstream. Our integrated modelling approach considers the seasonal variation of rainfall in the Ruvu catchment, showing that woody habitats play a significant role in regulating sediment load in rivers and reducing peak flows in high rainfall events. This has implications for the reliability of public water supply to Dar es Salaam and Morogoro from the Ruvu River. Retaining the forest and woodlands can help avoid costly deterioration in the public water supply to these two cities. This message aligns with the results of De Risi et al. (2018), who find that to avoid flood damages in Dar es Salaam, rehabilitation of the Msimbazi River catchment would have higher net benefits and a shorter payback period than other mitigation measures. Based on a combination of SWAT modelling and cost-based valuation, we find that the estimated cost savings of forest conservation under water treatment work conditions up to 2016 amount to USD 4.6-17.6 million per year for Dar es Salaam's population**.** An estimated additional cost saving of USD 308 thousand per year for maintenance of the Mindu Dam, which provides potable water to the population of Morogoro, could be realised by conservation of Ruvu's forests and woodlands.

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References

AAW, 2012. *Mindu Dam Design Report: Improvement of Water Supply and Sewerage Services in Morogoro Municipality*. Morogoro Tanzania: AAW Consulting Engineers.

AfDB, OECD, UNDP (African Development Bank, Organisation for Economic Co-operation and Development and United Nations Development Programme), 2014. *African economic outlook 2014*. Global value chains and Africa's industrialisation.

Africa Time, 2015. Water pumps valued at USD140000 to reduce Dar City water rationing. Available: http://en.africatime.com/articles/water-pumps-valued-usd140000-reduce-dar-city-water-rationing. [Accessed 11/05/2017]

Anderson, P. M., Okereke, C., Rudd, A., Parnell, S., 2013. Regional assessment of Africa, in: Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P.J., McDonald, R.I., Parnell, S., Schewenius, M., Sendstad, M., Seto, K. C. and Wilkinson, C. (Eds), *Urbanization, biodiversity and ecosystem services: Challenges and opportunities*: *a global assessment.* Springer, Dordrecht, pp. 453-459.

Arnaud, P., Bouvier, C., Cisneros, L., Dominguez, R., 2002. Influence of rainfall spatial variability on flood prediction. *Journal of Hydrology, 260*(1), 216-230.

Arnold, J., Kiniry, J., Srinivasan, R., Williams, J., Haney, E., Neitsch, S., 2011. Soil and Water Assessment Tool input/output file documentation: Version 2009. *Texas Water resources institute technical report, 365*.

Ashagre, B.B., 2009. *SWAT to identify watershed management options: Anjeni watershed, Blue Nile basin, Ethiopia*. Unpublished Masters Thesis, Cornell University, Cornell.

Ashagre, B.B., White, S., Balmford, A., Burgess, N., Matalo, F., Mwakalila, S., Platts, P., Schaafsma, M., Smith, C., Swetnam, R., 2014. Water to Everyone. *The Arc Journal,* (29), 15-18.

Bagstad, K., Villa, F., Batker, D., Harrison-Cox, J., Voigt, B., Johnson, G., 2014. From theoretical to actual ecosystem services: mapping beneficiaries and spatial flows in ecosystem service assessments. *Ecology and Society, 19*(2).

Baker, T.J., Miller, S.N., 2013. Using the Soil and Water Assessment Tool (SWAT) to assess land use impact on water resources in an East African watershed. *Journal of Hydrology, 486*, 100-111.

Balmford, A., Fisher, B., Green, R.E., Naidoo, R., Strassburg, B., Turner, R.K., Rodrigues, A.S., 2011. Bringing ecosystem services into the real world: an operational framework for assessing the economic consequences of losing wild nature. *Environmental and Resource Economics, 48*(2), 161-175.

Bayliss, K., Tukai, R., 2011. Services and supply chains: The role of the domestic private sector in water service delivery in Tanzania. United Nations Development Programme.

Betrie, G.D., Mohamed, Y.A., van Griensven, A., Srinivasan, R., 2011. Sediment management modelling in the Blue Nile Basin using SWAT model. *Hydrology and Earth System Sciences, 15*(3), 807.

Brauman, K.A., 2015. Freshwater, in: Potschin, M., Haines-Young, R., Fish, R., Turner, R.K. (Eds.), *Routledge Handbook of Ecosystem Services.* Routledge, pp. 374-382.

Brikké, F., Vairavamoorthy, K., 2016. Managing Change to Implement Integrated Urban Water Management in African Cities. *Aquatic Procedia, 6*, 3-14.

Bruijnzeel, L.A., 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture, Ecosystems & Environment, 104*(1), 185-228.

Burgess, N., Doggart, N., Lovett, J.C., 2002. The Uluguru Mountains of eastern Tanzania: the effect of forest loss on biodiversity. *Oryx, 36*(2), 140-152.

Burgess, N.D., Butynski, T.M., Cordeiro, N.J., Doggart, N.H., Fjeldså, J., Howell, K.M., Kilahama, F.B., Loader, S.P., Lovett, J.C., Mbilinyi, B., Menegon, M., Moyer, D.C., Nashanda, E., Perkin, A., Rovero, F., Stanley, W.T., Stuart, S.N., 2007. The biological importance of the Eastern Arc Mountains of Tanzania and Kenya. *Biological Conservation, 134*(2), 209-231.

Campbell, E.T., Tilley, D.R., 2014. Valuing ecosystem services from Maryland forests using environmental accounting. *Ecosystem Services, 7*, 141-151.

Coffey, M.E., Workman, S.R., Taraba, J.L., Fogle, A.W., 2004. Statistical procedures for evaluating daily and monthly hydrologic model predictions. *Transactions of the American Society of Agricultural Engineers, 47*(1), 59-68.

Cole, M.A., 2004. Economic growth and water use. *Applied Economics Letters*, *11*, 1-4.

Collier, S., Stockman, L., Hicks, L., Garrison, L., Zhou, F., Beach, M., 2012. Direct healthcare costs of selected diseases primarily or partially transmitted by water. *Epidemiology & Infection, 140*(11), 2003-2013.

Committee (on Standardization of Reference Evapotranspiration), 2002. The ASCE standardized reference evapotranspiration equation. *Environmental and Water Resources Institute of The American Society of Civil Engineers*.

Conway, D., Mittal, N., Vincent, K., 2017. Future Climate Projections for Tanzania. Future for Climate Africa.

Cui, X., Graf, H.F., Langmann, B., Chen, W., Huang, R., 2007. Hydrological impacts of deforestation on the southeast Tibetan Plateau. *Earth Interactions, 11*(15).

Cumming, G.S., Buerkert, A., Hoffmann, E.M., Schlecht, E., von Cramon-Taubadel, S., Tscharntke, T., 2014. Implications of agricultural transitions and urbanization for ecosystem services. *Nature, 515*, 50.

Cunha, D.G.F., Sabogal-Paz, L.P. and Dodds, W.K., 2016. Land use influence on raw surface water quality and treatment costs for drinking supply in São Paulo State (Brazil). *Ecological Engineering, 94*, 516-524.

Daily, G.C., Polasky, S., Goldstein, J., Kareiva, P.M., Mooney, H.A., Pejchar, L., Ricketts, T.H., Salzman, J., Shallenberger, R., 2009. Ecosystem services in decision making: time to deliver. *Frontiers in Ecology and the Environment, 7*(1), 21-28.

DAWASCO (Dar es Salaam Water and Sanitation Corporation), 2013. *DAWASCO Water Tarrifs*, Available: http://www.dawasco.com/tarrifs.php [Accessed 09/10 2015].

De Risi, R., De Paola, F., Turpie, J., Kroeger, T., 2018. Life Cycle Cost and Return on Investment as complementary decision variables for urban flood risk management in developing countries. *International Journal of Disaster Risk Reduction, 28*, 88-106.

Dennedy-Frank, P.J., Muenich, R.L., Chaubey, I., Ziv, G., 2016. Comparing two tools for ecosystem service assessments regarding water resources decisions. *Journal of Environmental Management, 177*, 331-340.

Dessu, S.B., Melesse, A.M., 2013. Impact and uncertainties of climate change on the hydrology of the Mara River basin, Kenya/Tanzania. *Hydrological Processes, 27*(20), 2973-2986.

Dile, Y.T., Srinivasan, R., 2014. Evaluation of CFSR climate data for hydrologic prediction in data-scarce watersheds: an application in the Blue Nile River Basin. *JAWRA Journal of the American Water Resources Association, 50*(5), 1226-1241.

Dos Santos, S., Adams, E. A., Neville, G., Wada, Y., de Sherbinin, A., Mullin Bernhardt, E. and Adamo, S. B. (2017) Urban growth and water access in sub-Saharan Africa: Progress, challenges, and emerging research directions. *Science of The Total Environment, 607-608*, pp. 497-508.

Dupont, D.P., Jahan, N., 2012. Defensive spending on tap water substitutes: the value of reducing perceived health risks. *Journal of Water and Health, 10*(1), 56-68.

Easton, Z., Fuka, D., White, E., Collick, A., Ashagre, B., McCartney, M., Awulachew, S., Ahmed, A., Steenhuis, T., 2010. A multi basin SWAT model analysis of runoff and sedimentation in the Blue Nile, Ethiopia. *Hydrology and Earth System Sciences, 14*(10), 1827-1841.

Ellison, D., N Futter, M., Bishop, K., 2012. On the forest cover–water yield debate: from demand-to supply-side thinking. *Global Change Biology, 18*(3), 806-820.

EWURA, 2013. *Water Utilities Performance Report 2012/13: Regional Water Utilities and DAWASCO Energy and Water Utilities Regulatory Authority (EWURA)*. Dar es Salaam, Tanzania.

Fisher, B., Lewis, S.L., Burgess, N.D., Malimbwi, R.E., Munishi, P.K., Swetnam, R.D., Turner, R.K., Willcock, S., Balmford, A., 2011. Implementation and opportunity costs of reducing deforestation and forest degradation in Tanzania. *Nature Climate Change, 1*(3), 161.

Fisher, J.R.B., Acosta, E.A., Dennedy-Frank, P.J., Kroeger, T., Boucher, T.M., 2017. Impact of satellite imagery spatial resolution on land use classification accuracy and modeled water quality. *Remote Sensing in Ecology and Conservation*, 1-13.

Francesconi, W., Srinivasan, R., Pérez-Miñana, E., Willcock, S.P., Quintero, M., 2016. Using the Soil and Water Assessment Tool (SWAT) to model ecosystem services: A systematic review. *Journal of Hydrology, 535*, 625-636.

GLOWS-FIU, 2014. *Climate, Forest Cover, and Water Resources Vulnerability: Wami/Ruvu Basin, Tanzania*. Miami, Florida, USA: Florida International University.

Gómez-Baggethun, E., Gren, Å., Barton, D.N., Langemeyer, J., McPhearson, T., O'Farrell, P., Andersson, E., Hamstead, Z., Kremer, P., 2013. Urban ecosystem services, in: Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P.J., McDonald, R.I., Parnell, S., Schewenius, M., Sendstad, M., Seto, K.C., Wilkinson, C. (Eds), *Urbanization, biodiversity and ecosystem services: Challenges and opportunities*. Springer, Dordrecht, pp. 175-251.

Gondwe, E., 2000. Sediment Transport of Ruvu River in Tanzania. *Discovery and Innovation, 12*(3-4), 118-127.

Grayson, R.B., Finlayson, B.L., Gippel, C.J., Hart, B.T., 1996. The Potential of Field Turbidity Measurements for the Computation of Total Phosphorus and Suspended Solids Loads. *Journal of Environmental Management, 47*(3), 257-267.

Green, J.M., Burgess, N.D., Green, R.E., Madoffe, S.S., Munishi, P.K., Nashanda, E., Turner, R.K., Balmford, A., 2012. Estimating management costs of protected areas: a novel approach from the Eastern Arc Mountains, Tanzania. *Biological Conservation*, *150*(1), 5-14.

Green, J.M., Larrosa, C., Burgess, N.D., Balmford, A., Johnston, A., Mbilinyi, B.P., Platts, P.J., Coad, L., 2013. Deforestation in an African biodiversity hotspot: Extent, variation and the effectiveness of protected areas. *Biological Conservation, 164*, 62-72.

Guswa, A.J., Brauman, K.A., Brown, C., Hamel, P., Keeler, B.L., Sayre, S.S., 2014. Ecosystem services: Challenges and opportunities for hydrologic modeling to support decision making. *Water Resources Research, 50*(5), 4535-4544.

Haase, D., Tötzer, T., 2012. Urban–rural linkages—analysing, modelling, and understanding drivers, pressures, and impacts of land use changes along the rural-to-urban gradient. *Environment and Planning B: Planning and Design*, *39*,194-197.

Hall, J., Burgess, N.D., Lovett, J., Mbilinyi, B., Gereau, R.E., 2009. Conservation implications of deforestation across an elevational gradient in the Eastern Arc Mountains, Tanzania. *Biological Conservation, 142*(11), 2510-2521.

Hathout, S.A., 1983. *Soil atlas of Tanzania.* Tanzania Publishing House.

Heckmann, M., 2014. Farmers, smelters and caravans: Two thousand years of land use and soil erosion in North Pare, NE Tanzania. *Catena, 113*, 187-201.

Heuvelmans, G., Muys, B., Feyen, J., 2004. Evaluation of hydrological model parameter transferability for simulating the impact of land use on catchment hydrology. *Physics and Chemistry of the Earth, Parts A/B/C, 29*(11), 739-747.

Holmes, T.P., 1988. The offsite impact of soil erosion on the water treatment industry. *Land Economics, 64*(4), 356-366.

Huisman, J., Breuer, L., Eckhardt, K., Frede, H.-G., 2003. Spatial consistency of automatically calibrated SWAT simulations in the Dill catchment and three of its sub-catchments, in: *Proceedings of the 2nd International SWAT Conference*, pp. 1-4.

Hutchinson, M., 1999. ANUSPLIN User Guide Version 4.0 Centre for Resource and Environmental Studies. *Australian National University, Canberra*.

IFRC (International Federation of Red Cross and Red Crescent Societies), 2011. *Disaster relief emergency fund (DREF) Tanzania: floods*, Available: http://www.ifrc.org/docs/appeals/11/MDRTZ013.pdf [Accessed 11 October 2015].

IPS (Inter Press Service), 2009. *TANZANIA: Solutions to Dar's Water Problems in the Pipeline*, Available: http://www.ipsnews.net/2009/08/tanzania-solutions-to-dar39s-water-problems-in-the-pipeline/ [Accessed 09/10/2015].

Itani, J. (1998) Evaluation of an Indigenous Farming Systems in the Matengo Highlands, Tanzania, and Its Sustainability.

JICA (Japan International Cooperation Agency), 2013. *The Study on Water Resource Management and Development in Wami/Ruvu Basin in the United Republic of Tanzania*: Japan International Cooperation Agency.

Kaczan D., Swallow B., Adamowicz W.L., Vihemäki H., 2012. Designing an incentive programme to reduce on-farm deforestation in the East Usambara Mountains, Tanzania. ICRAF Working Paper no 145, Nairobi, World Agroforestry Centre.

Kalugendo, P., 2008. Impacts of climate variability on ground water in Dar es Salaam, Tanzania. in: *Proceedings of the International Conference Groundwater and Climate in Africa, Kampala, Uganda,* pp 52.

Kato, M., 2001. Intensive cultivation and environment use among the Matengo in Tanzania. *African Study Monographs, 22*(2), 73-92.

Keeler, B.L., Polasky, S., Brauman, K.A., Johnson, K.A., Finlay, J.C., O'Neill, A., Kovacs, K., Dalzell, B., 2012. Linking water quality and well-being for improved assessment and valuation of ecosystem services. *Proceedings of the National Academy of Sciences, 109*(45), 18619-18624.

Kimaro, D., Msanya, B., Mwango, S., Kimbi, G., Kileo, E., 2001. *Soils and Land Resources Report of Morogoro Urban District, Tanzania*. Land resources inventory and suitability assessment for the production of the major crops in the eastern part of Morogoro rural district, Tanzania. Department of Soil Science, Faculty of Agriculture, Sokoine University of Agriculture.

Kimaro, D.N., Poesen, J., Msanya, B.M., Deckers, J.A., 2008. Magnitude of soil erosion on the northern slope of the Uluguru Mountains, Tanzania: Interrill and rill erosion. *Catena, 75*(1), 38-44.

Kjellén, M., 2006. *From public pipes to private hands: Water access and distribution in Dar es Salaam, Tanzania*. Unpublished.

Larsen, T. A., Hoffmann, S., Lüthi, C., Truffer, B. and Maurer, M. (2016) Emerging solutions to the water challenges of an urbanizing world. *Science*, *352*(6288), pp. 928-933.

Lele, S., 2009. Watershed services of tropical forests: from hydrology to economic valuation to integrated analysis. *Current Opinion in Environmental Sustainability, 1*(2), 148-155.

Lopa, D., Mwanyoka, I., Jambiya, G., Massoud, T., Harrison, P., Ellis-Jones, M., Blomley, T., Leimona, B., van Noordwijk, M., Burgess, N.D., 2012. Towards operational payments for water ecosystem services in Tanzania: a case study from the Uluguru Mountains. *Oryx, 46*(01), 34-44.

Lundgren, B., 1978. *Soil conditions and nutrient cycling under natural and plantation forests in Tanzanian highlands.* Swedish University of Agricultural Sciences.

Maes, J., Egoh, B., Willemen, L., Liquete, C., Vihervaara, P., Schägner, J. P., Grizzetti, B., Drakou, E.G., La Notte, A., Zulian, G., 2012. Mapping ecosystem services for policy support and decision making in the European Union. *Ecosystem Services, 1*(1), 31-39.

Mango, L.M., Melesse, A.M., McClain, M.E., Gann, D., Setegn, S.G., 2011. Hydro-meteorology and water budget of the Mara River Basin under land use change scenarios, in: Melesse, A.M. (Ed.), *Nile River Basin; Hydrology, Climate and Water Use.* Springer, 39-68.

Mbogoni, J., Kwacha, J., Urassa, G., Nyaki, A., 2005. *Suitability Assessment of Soils and Climate for Production off Yelloe Passsion fruit at Mpiji Farm Kibaha District, Coast Region*. Tanga, Tanzania: Mlingano Agricultural Research Institute.

McDonald, R.I., Marcotullio, P.J., Güneralp, B., 2013. Urbanization and global trends in biodiversity and ecosystem services, in: Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P.J., McDonald, R.I., Parnell, S., Schewenius, M., Sendstad, M., Seto, K.C., Wilkinson, C. (Eds), *Urbanization, biodiversity and ecosystem services: Challenges and opportunities*: *a global assessment.* Springer, Dordrecht, pp. 31-52.

Meena, H., Sharif, S., 2008. Analysis of Technical and Policy Options for Adaptation to Consequences of Climate Change for Tanzania. *Gender, Poverty, and Food Security in Relation to Climate Change Impact and Adaptation, a case of Kilimanjaro Region.* Netherlands Climate Change Assistance Programme (NCAP), Tanzania, 432-468.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE, 50*(3), 885-900.

MORUWASA (Morogoro Urban Water and Sewerage Authority), 2017. *MORUWASA'S Strategic Plan Matrix for 2007/2008 – 2021/2022*, Available: http://moruwasa.go.tz/downloads/Moruwasa%20Stategic%20Plan%20Matrix%20form.pdf [Accessed 12/12 2017].

MORUWASA (Morogoro Urban Water and Sewerage Authority), 2009. *Annual Progress Report July 2008 to June 2009.* Morogoro Urban Water and Sewerage Authority, Morogoro, Tanzania.

Msanya, B., Kimaro, D., Kileo, E., Kimbi, G., Munisi, A.M., 2001. *Soils and Land Resources Report of Morogoro Urban District, Tanzania*. Land resources inventory and suitability assessment for the production of the major crops in the eastern part of Morogoro rural district, Tanzania: Department of Soil Science, Faculty of Agriculture, Sokonie University of Agriculture.

Mtoni, Y.E., Mjemah, I., Msindai, K., Van Camp, M., Walraevens, K., 2012. Saltwater intrusion in the Quaternary aquifer of the Dar es Salaam region, Tanzania. *Geologica Belgica, 15*(1-2), 16-25.

Mwakalila, S., 2007. Residents' perceptions of institutional performance in water supply in Dar es Salaam. *Physics and Chemistry of the Earth, Parts A/B/C, 32*(15), 1285-1290.

National Bureau of Statistics, 2009. Household Budget Survey 2007 - Final Report. National Bureau of Statistics, Tanzania.

National Water Policy, 2002. *Ministry of Water and Livestock Development*. Dar es Salaam, Tanzania.

Natkhin, M., Dietrich, O., Schäfer, M.P., Lischeid, G., 2015. The effects of climate and changing land use on the discharge regime of a small catchment in Tanzania. *Regional Environmental Change, 15*(7), 1269-1280.

Nauges, C., Whittington, D., 2010. Estimation of water demand in developing countries: An overview. *The World Bank Research Observer, 25*(2), 263-294.

Ndomba, P., Mtalo, F., Killingtveit, A., 2008. SWAT model application in a data scarce tropical complex catchment in Tanzania. *Physics and Chemistry of the Earth, Parts A/B/C, 33*(8), 626-632.

Neitsch, S., Arnold, J., Kiniry, J., Williams, J., King, K., 2005. Soil and water assessment tool theoretical documentation. Grassland. *Soil and Water Research Laboratory, Temple, TX*.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. *Soil and water assessment tool theoretical documentation version 2009*: Texas Water Resources Institute.

Newmark, W.D., 2002. *Conserving biodiversity in East African forests: a study of the Eastern Arc Mountains.* Springer Science & Business Media.

Ngana, J., Mahay, F., Cross, K., 2010. *Ruvu Basin: A situation analysis,* IUCN.

Nganyanyuka, K., Martinez, J., Wesselink, A., Lungo, J.H., Georgiadou, Y., 2014. Accessing water services in Dar es Salaam: Are we counting what counts? *Habitat International, 44*, 358-366.

Ngonyani, C.J., Nkotagu, H.H., 2007. Study of nutrient pollutants and their impacts on the water quality of the Mindu reservoir at Morogoro. *College of Engineering and Technology University of Dar es Salaam*, pp. 139.

Nicholson, S.E., 1996. A review of climate dynamics and climate variability in Eastern Africa, in: Johnson, T.C., Odada, E.O., *The limnology, climatology and paleoclimatology of the East African lakes*. Gordon and Breach Publishers, pp. 25-56.

Nobert, J., Skinner, J., 2016. *Meeting future demand for drinking water supply in Dar es Salaam: Hydrological modelling of the Ruvu River and assessment of flows*. IIED Working Paper. London: IIED.

Noll, R., Shirley, M.M., Cowan, S., 2000. Reforming urban water systems in developing countries, in: Krueger, A.O. (Ed.), *Economic policy reform: The second stage*, pp. 243-289.

Notter, B., Hurni, H., Wiesmann, U., Abbaspour, K., 2012. Modelling water provision as an ecosystem service in a large East African river basin. *Hydrology and Earth System Sciences, 16*(1), 69-86.

Nyeko, M., 2015. Hydrologic modelling of data scarce basin with SWAT model: capabilities and limitations. *Water Resources Management, 29*(1), 81-94.

Office of the Chief Government Statistician, 2013. *Population and Housing Census: Population Distribution by Administrative Units; Key findings*. Dar es Salaam, Tanzania: National Bureau of Statistics (NBS) and Office of the Chief Government Statistician.

Ogallo, L., 1989. The spatial and temporal patterns of the East African seasonal rainfall derived from principal component analysis. *International Journal of Climatology, 9*(2), 145-167.

Pandeya, B., Buytaert, W., Zulkafli, Z., Karpouzoglou, T., Mao, F., Hannah, D., 2016. A comparative analysis of ecosystem services valuation approaches for application at the local scale and in data scarce regions. *Ecosystem Services, 22*, 250-259.

Platts, P. J., Burgess, N.D., Gereau, R.E., Lovett, J.C., Marshall, A.R., McClean, C.J., Pellikka, P.K.E., Swetnam, R.D., Marchant, R., 2011. Delimiting tropical mountain ecoregions for conservation. *Environmental Conservation, 38*(3), 312-324.

Ponette-González, A.G., Brauman, K.A., Marín-Spiotta, E., Farley, K.A., Weathers, K.C., Young, K.R., Curran, L.M., 2015. Managing water services in tropical regions: From land cover proxies to hydrologic fluxes. *Ambio, 44*(5), 367-375.

Reweta, W., Sampath, R., 2000. Performance evaluation of urban water supply in Tanzania: the case of Dar es Salaam city. *International Journal of Water Resources Development, 16*(3), 407-421.

Römkens, M.J., Helming, K., Prasad, S., 2002. Soil erosion under different rainfall intensities, surface roughness, and soil water regimes. *Catena, 46*(2), 103-123.

Rostapshova, O., Roumis, D., Duthie, M., Alwang, J., 2014. Impacts of an urban water system investment on health, well-being and poverty. in: *11th Annual IWREC Meeting*. World Bank Headquarters, Washington D.C.

Rovero, F., Menegon, M., Fjeldså, J., Collett, L., Doggart, N., Leonard, C., Norton, G., Owen, N., Perkin, A., Spitale, D., 2014. Targeted vertebrate surveys enhance the faunal importance and improve explanatory models within the Eastern Arc Mountains of Kenya and Tanzania. *Diversity and Distributions, 20*(12), 1438-1449.

Rozario, P.F., Oduor, P., Kotchman, L., Kangas, M., 2016. Quantifying Spatiotemporal Change in Landuse and Land Cover and Accessing Water Quality: A Case Study of Missouri Watershed James Sub-Region, North Dakota. *Journal of Geographic Information System, 8*(06), 663.

Sahin, V., Hall, M.J., 1996. The effects of afforestation and deforestation on water yields. *Journal of Hydrology, 178*(1), 293-309.

Salman, M., Martinez, A., 2015. Water for agriculture and energy, in: Martin-Ortega, J., Ferrier, R.C., Gordon, I.J. and Khan, S. (Eds.), *Water Ecosystem Services: A Global Perspective*. Cambridge University Press, pp. 35-45.

Schaafsma, M., Ferrini, S., Harwood, A. R., Bateman, I.J., 2015. The first United Kingdom's national ecosystem assessment and beyond, in: Martin-Ortega, J., Ferrier, R.C., Gordon, I.J. and Khan,

S. (Eds.), *Water Ecosystem Services: A Global Perspective*. Cambridge University Press, pp. 73-81.

Sharpley, A.N., Williams, J.R., 1990. EPIC, Erosion/Productivity Impact Calculator. *Technical bulletin (USA)*.

Sharps, K., Masante, D., Thomas, A., Jackson, B., Cosby, B., Emmett, B., Jones, L., 2017. Comparing strengths and weaknesses of three ecosystem services modelling tools in a diverse UK river catchment. *Science of The Total Environment, 584-585*, 118-130.

Smiley, S.L., 2013. Complexities of water access in Dar es Salaam, Tanzania. *Applied Geography, 41*, 132-138.

Spellman, F. R. (2008) *Handbook of water and wastewater treatment plant operations,* CRC Press.

Spooner, R., Jenkin, R.N., 1966. The development of the lower Mgeta River Area of the United Republic of Tanzania. Land Resources Division, Directorate of Overseas Surveys, England.

Sthiannopkao, S., Takizawa, S., Homewong, J., Wirojanagud, W., 2007. Soil erosion and its impacts on water treatment in the northeastern provinces of Thailand. *Environment International, 33*(5), 706-711.

Swetnam, R., Fisher, B., Mbilinyi, B., Munishi, P., Willcock, S., Ricketts, T., Mwakalila, S., Balmford, A., Burgess, N., Marshall, A., 2011. Mapping socio-economic scenarios of land cover change: A GIS method to enable ecosystem service modelling. *Journal of Environmental Management, 92*(3), 563-574.

Terrado, M., Acuña, V., Ennaanay, D., Tallis, H., Sabater, S., 2014. Impact of climate extremes on hydrological ecosystem services in a heavily humanized Mediterranean basin. *Ecological Indicators, 37*, 199-209.

Thompson, J., Porras, I.T., Wood, E., Tumwine, J.K., Mujwahuzi, M.R., Katui-Katua, M., Johnstone, N., 2000. Waiting at the tap: Changes in urban water use in East Africa over three decades. *Environment and Urbanization, 12*(2), 37-52.

Uhrich, M.A., Bragg, H.M., 2003. *Monitoring instream turbidity to estimate continuous suspended-sediment loads and yields and clay-water volumes in the upper North Santiam River Basin, Oregon, 1998-2000*.

Uwasi, 2010. *Water prices in Dar es Salaam Do water kiosks comply with official tariffs? Policy brief TZ.09/2010E. Released September 2010*. Uwasi, Dar es Salaam, Tanzania.

Van Camp, M., Mtoni, Y., Mjemah, I.C., Bakundukize, C., Walraevens, K., 2014. Investigating seawater intrusion due to groundwater pumping with schematic model simulations: The example of the Dar es Salaam coastal aquifer in Tanzania. *Journal of African Earth Sciences, 96*, 71-78.

Van der Ploeg, S., De Groot, R., 2010. The TEEB Valuation Database–a searchable database of 1310 estimates of monetary values of ecosystem services. *Foundation for Sustainable Development, Wageningen, The Netherlands*.

van Griensven, A., Popescu, I., Abdelhamid, M., Ndomba, P.M., Beevers, L., Betrie, G.D., 2013. Comparison of sediment transport computations using hydrodynamic versus hydrologic models in the Simiyu River in Tanzania. *Physics and Chemistry of the Earth, Parts A/B/C, 61*, 12-21.

Vigerstol, K.L., Aukema, J.E., 2011. A comparison of tools for modeling freshwater ecosystem services. *Journal of Environmental Management, 92*(10), 2403-2409.

Villamagna, A.M., Angermeier, P.L., Bennett, E.M., 2013. Capacity, pressure, demand, and flow: A conceptual framework for analyzing ecosystem service provision and delivery. *Ecological Complexity, 15*, 114-121.

Vogl, A.L., Bryant, B.P., Hunink, J.E., Wolny, S., Apse, C., Droogers, P., 2017. Valuing investments in sustainable land management in the Upper Tana River basin, Kenya. *Journal of Environmental Management, 195*, 78-91.

Wambura, F.J., Ndomba, P.M., Kongo, V., Tumbo, S.D., 2015. Uncertainty of runoff projections under changing climate in Wami River sub-basin. *Journal of Hydrology: Regional Studies, 4*, 333-348.

WaterAid-Tanzania, Tearfund, 2003. *Water reforms and PSP in Dar es Salaam: New Rules, New Roles: Does PSP Benefit the Poor?* WaterAid-Tanzania.

Williams, J.R., Singh, V., 1995. The EPIC model. *Computer models of watershed hydrology*, 909-1000.

Wischmeir, W.H., 1965. Predicting Rainfall-Erosion Losses from Cropland East of the Rocky Mountain, Guide for Selection of Practices for Soil and Water Conservation. *Agricultural handbook*, *282*.

Yanda, P.Z., Munishi, P., 2007. Hydrologic and land use/cover change analysis for the Ruvu River (Uluguru) and Sigi River (East Usambara) watersheds. WWF/CARE Dar es Salaam, Tanzania.

Zivin, J. G., Neidell, M., Schlenker, W., 2011. Water quality violations and avoidance behavior: Evidence from bottled water consumption. *American Economic Review, 101*(3), 448-53.

Appendix 1. Soil, land cover and rainfall data

Soil data

The Ruvu catchment (Figure 1) lies between 37^0 16' E – 38^0 57' E and 7^0 48' S - 6^0 26' S. The Ruvu catchment has 16 different types of soils (Hathout 1983); much of the catchment has a sandy clay loam soil texture that covers almost the entire Uluguru Mountains, while the lower elevation with a gentle slope in the catchment has a loamy fine sand texture. Most soil types are sensitive to soil erosion due to their texture. The Mindu Reservoir is located located 500 m above sea level, between latitudes 6^{o}51' S to 6^{o}52' S and longitudes 37^{o}30' E to 37^{o}40' E, southeast of the Ngerengere River. The drainage area to Mindu Reservoir measures 30,800 ha and is largely mountainous with a slope greater than 15% covering 46% of the area, and areas with a slope less than 6% covering 37% of the area.

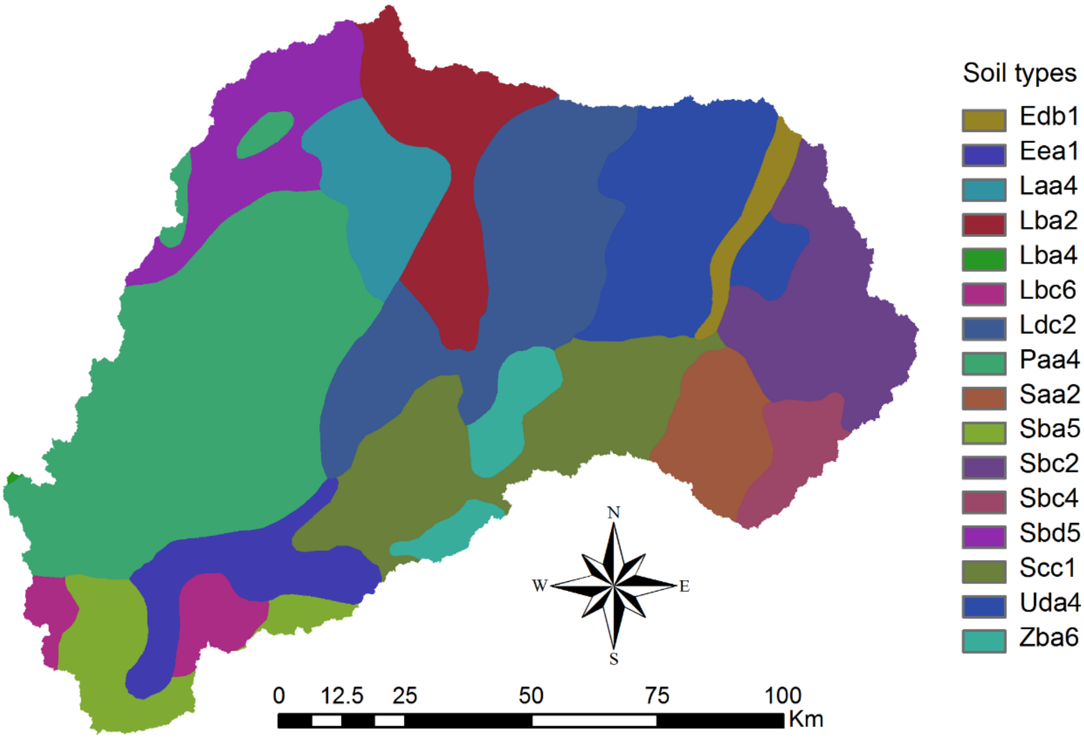

Figure A1.1: Soil map of the Ruvu catchment based on Hathout (1983)

Table A1.1. Ruvu soil map and profile details based on Hathout (1983), Kimaro et al. (2001), Lundgren (1978), Msanya et al. (2001)

Soil name	Number of soil layers	Soil maximum depth	Soil texture of each layer	Soil hydrologic group
Edb1	4	850	C-C-C-C	D
Eea1	4	1200	SCL-CL-C-C	C
Lba2	5	1100	SL-SL-SL-SL-SL	A
Lba4	3	700	SL-SCL-SCL	B
Lbc6	6	1900	SL-SCL-SCL-CL-CL-L	B
Ldc2	4	1050	SC-SC-SC-SC	C
Paa4	3	900	SL-SCL-SCL	B
Saa2	5	1200	LS-LS-LS-LS-LS	A
Sba5	5	1100	SCL-SC-C-C-C	B
Sbc2	6	2000	LS-LS-SL-SL-SL-SL	B
Sbc4	6	1200	LS-LS-LS-LS-LS-LS	A
Sbd5	6	1260	LS-SL-SL-SL-SCL-SL	A
Scc1	6	1340	CL-SL-CL-L-CL-SL	B
Uda4	7	1300	SCL-SC-SC-C-C-SC-SCL	C
Zba6	5	1100	SL-SL-SCL-SCL-SC	B

C=clay, S=sandy, and L=loamy - Based on Natural Resources Conservation Service (NRCS) soil classification

Soil infiltration rate when thoroughly wet: A – high, B – moderate, C – slow, D – very slow

Land cover data

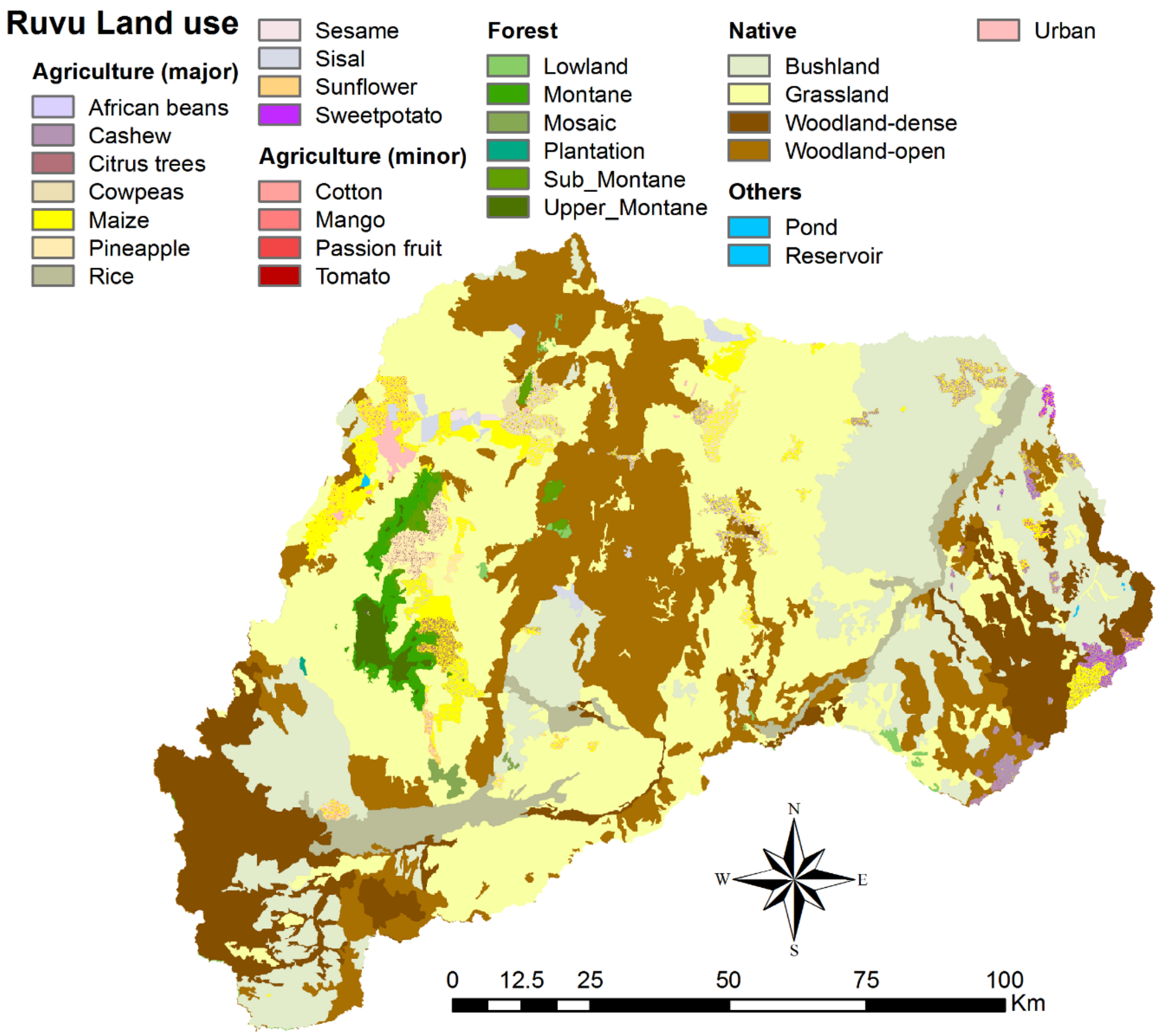

Figure A1.2: Land use map of the Ruvu catchment based on Swetnam et al. (2011).

Rainfall data

There were 19 rainfall stations within the Ruvu catchment (see Fig. A1.3), out of which only seven stations have a significant amount of data for the period 1995 – 2005 (see Table A1.2). The period 1995 -2005 was of most interest in this study since the land use map available for use was representative for the year 2000 (Swetnam et al. 2011).

These seven stations provided insufficient data, however, to run the model due to the highly spatial variation of rainfall pattern and amount (Nicholson 1996, Ogallo 1989). Hence, we used the WXGEN weather generator incorporated in SWAT (Neitsch et al. 2011) to generate rainfall data for those stations which have solid historical rainfall data but no data in the period 1995 – 2004. We also used the weather generator to fill gaps in the data from the seven stations.

We used daily minimum and maximum temperature data from the Morogoro Hydro-meteorological station and Dar es Salaam Meteorology head office, together with extra-terrestrial radiation, to estimate the solar radiation using a similar approach as Hargreaves-Samani as presented in Committee (2002).

We generated further daily climatic data using the WXGEN weather generator. The input for the WXGEN weather generator include average monthly precipitation, monthly maximum and minimum temperatures along with their standard deviations, and monthly precipitation with its standard deviation, skewness, wet day/dry day probabilities taken from the grid surface developed by Texas A&M University. The grid surface was developed using climate data from the World Meteorological Organization (WMO) database for Eastern Africa for the period of 1975 to 2001. These datasets were used to derive coefficients for parameterizing the WXGEN weather generator using the WXPARM program developed by TAMU Blacklands Research Centre (Sharpley and Williams 1990). The WXGEN coefficients were entered into the ANUSPLIN software to create gridded surfaces of each coefficient (Hutchinson 1999).

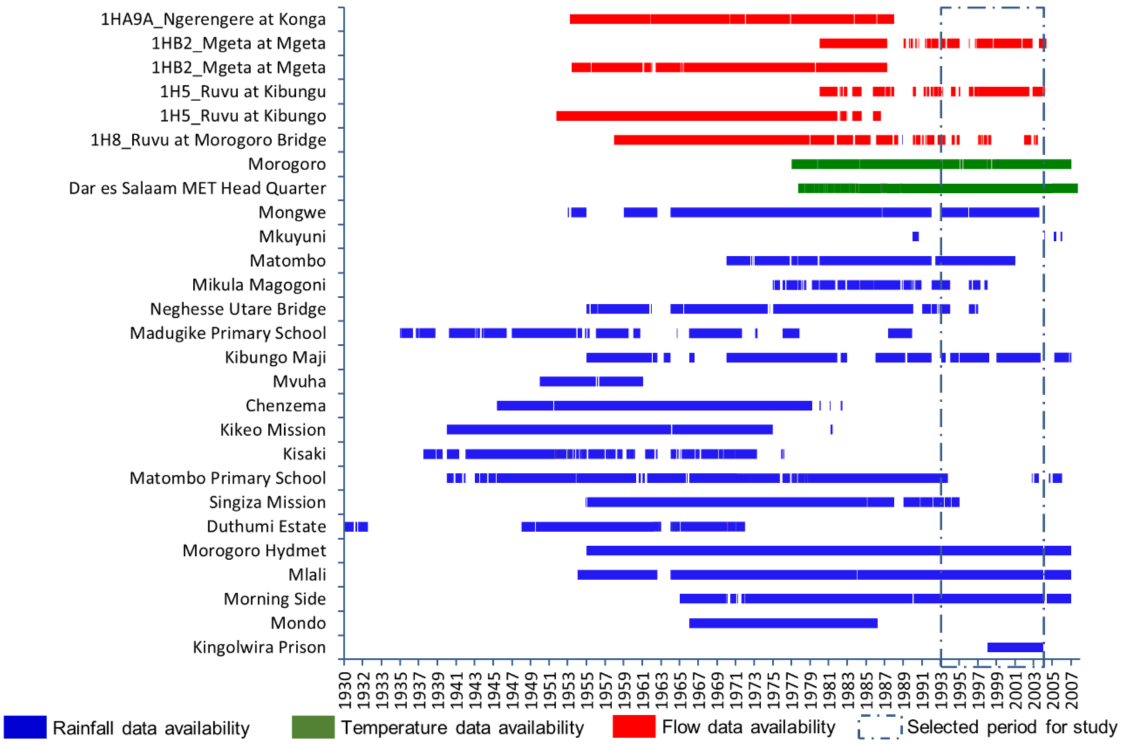

Figure A1.3: Measured data availability for Ruvu Catchment

Table A1.2. Rain fall stations used in SWAT model setup

Rainfall Stations with significant amount of data for the period 1995 - 2004	Rainfall stations with solid historical data	Stations with very few data
Kibungu Maji	Chenzema	Mikula Magogoni
Matombo Primary School	Duthumi Estate	Neghesse Utari bridge
Mondo	Kikeo Mission	Singiza Mission
Mongwe	Kisaki Mission	
Kingolwira Prison	Madugiki Primary School	
Morogoro Hydmet	Mvuha	
Morningside		

SWAT crop database

Table A1.3 Crop database for SWAT

CPNM	IDC	CROPNAME	BIO_E	HVSTI	BLAI	FRGRW1	LAIMX1	FRGRW2	LAIMX2	DLAI	CHTMX	RDMX	T_OPT	T_BASE	CNYLD	CPYLD
PNPL	6	Pineapple	22	0.55	6.8	0.14	0.19	0.45	0.93	0.99	1.2	0.85	29.5	9	0.0078	0.0016
SSME	4	Sesame	30	0.49	4.4	0.15	0.11	0.44	0.8	0.74	1.42	2.4	27	15.6	0.06	0.009
MNGO	7	Mango	23	0.14	3.5	0.1	0.15	0.5	0.75	0.99	20	6	27	10	0.013	0.005
CSHW	7	Cashew	21	0.08	3.5	0.1	0.15	0.5	0.75	0.99	15	3	27	15	0.013	0.005
PSSF	7	Passion fruit	15	0.05	4	0.1	0.15	0.5	0.75	0.99	10	2	23	2	0.0019	0.0004
CTRS	7	Citrus trees	18	0.3	4	0.1	0.15	0.5	0.75	0.99	10	2.5	25	10	0.032	0.002
WDCL	7	Dense Woodland	16.1	0.0045	5.5	0.1	0.7	0.4	0.95	0.99	18	3.7	23	9	0.0015	0.0003
CSIS	6	Sisal	25	0.55	5	0.15	0.02	0.5	0.8	0.9	5	2	30	16	0.04	0.0033
BSHL	7	Bushland	16.1	0.05	4	0.05	0.05	0.4	0.95	0.99	10	2	25	9	0.0015	0.0003
FPLT	7	Plantation Forest	30	0.01	6	0.05	0.05	0.4	0.95	0.99	20	3.5	28	8	0.0015	0.0003
DRGL	6	Dry Grassland	34	0.9	3.5	0.05	0.1	0.3	0.8	0.9	1	2	25	9	0.016	0.0022
ABEN	1	African Bean	25	0.3	3	0.15	0.01	0.5	0.95	0.8	0.6	2	28	15	0.0368	0.0046
FUMN	7	Upper Montane Forest	20	0.0018	6	0.1	0.7	0.4	0.99	0.99	15	6	15	4	0.0015	0.0003
FMNT	7	Montane Forest	18	0.0016	6.5	0.1	0.7	0.4	0.95	0.99	21	4	21	4	0.0015	0.0003
FSMN	7	Sub-Montane Forest	16	0.0013	6.8	0.1	0.7	0.4	0.99	0.99	30	6	22	6	0.0015	0.0003
FLLD	7	Lowland Forest	15	0.0027	6	0.1	0.7	0.4	0.99	0.99	42	6	23	9	0.0015	0.0003
FMSC	7	Mosaic Forest	15	0.003	5.5	0.1	0.7	0.4	0.99	0.99	30	5	23	9	0.0015	0.0003
WDOP	7	Open Woodland	16.1	0.0093	4.5	0.1	0.7	0.4	0.95	0.99	15	3.7	24	9.5	0.0015	0.0003

CPNM	BN1	BN2	BN3	BP1	BP2	BP3	WSYF	USLE_C	GSI	VPDFR	FRGMAX	WAVP	CO2HI	BIOEHI
PNPL	0.016	0.0148	0.01	0.004	0.0015	0.00128	0.265	0.17	0.0014	4	0.75	6	660	27.5
SSME	0.035	0.0132	0.01	0.0062	0.0023	0.0018	0.2	0.39	0.011	4	0.75	7	660	35
MNGO	0.04	0.013	0.01	0.0019	0.001	0.0008	0.06	0.12	0.007	4	0.75	3	660	30
CSHW	0.004	0.0013	0	0.00019	0.00012	0.0001	0.01	0.12	0.007	4	0.75	3	660	25
PSSF	0.006	0.002	0	0.0007	0.0004	0.0003	0.03	0.22	0.007	4	0.75	3	660	20
CTRS	0.008	0.003	0	0.0003	0.00015	0.00012	0.08	0.12	0.007	4	0.75	3	660	23
WDCL	0.006	0.002	0	0.0007	0.0004	0.0003	0.001	0	0.004	4	0.75	8	660	18
CSIS	0.048	0.0294	0.03	0.0049	0.0024	0.0023	0.4	0.2	0.005	4	0.75	10	660	33
BSHL	0.006	0.002	0	0.0007	0.0004	0.0003	0.01	0	0.004	4	0.75	8	660	18
FPLT	0.006	0.002	0	0.0007	0.0004	0.0003	0.001	0	0.004	4	0.75	8	660	31
DRGL	0.02	0.012	0.01	0.0014	0.001	0.0007	0.9	0.15	0.005	4	0.75	10	660	39
ABEN	0.004	0.003	0	0.0035	0.003	0.0015	0.22	0.4	0.005	4	0.75	5	660	34
FUMN	0.006	0.002	0	0.0007	0.0004	0.0003	0.03	0	0.002	4	0.75	8	660	20
FMNT	0.006	0.002	0	0.0007	0.0004	0.0003	0.03	0	0.004	4	0.75	8	660	19
FSMN	0.006	0.002	0	0.0007	0.0004	0.0003	0.03	0	0.002	4	0.75	8	660	18
FLLD	0.006	0.002	0	0.0007	0.0004	0.0003	0.06	0	0.002	4	0.75	8	660	17
FMSC	0.006	0.002	0	0.0007	0.0004	0.0003	0.01	0	0.002	4	0.75	8	660	16
WDOP	0.006	0.002	0	0.0007	0.0004	0.0003	0.05	0.08	0.004	4	0.75	8	660	18

CPNM	RSDCO_PL	OV_N	CN2A	CN2B	CN2C	CN2D	FERTFIELD	ALAI_MIN	BIO_LEAF	MAT_YRS	BMX_TREES	EXT_COEF	BM_DIEOFF
PNPL	0.06	0.14	43	58	68	74	1	5	0	0	0	0.65	0.1
SSME	0.099	0.14	67	77	83	87	1	0	0	0	0	0.65	0.1
MNGO	0.05	0.15	54	66	77	83	1	3	0.1	10	650	0.65	0.1
CSHW	0.05	0.15	54	66	77	83	1	3	0.1	6	500	0.65	0.1
PSSF	0.05	0.15	54	66	77	83	1	3	0.1	10	280	0.65	0.1
CTRS	0.05	0.14	43	63	73	79	1	3	0.1	6	380	0.65	0.1
WDCL	0.05	0.18	40	55	70	77	0	4.5	0.05	99	250	0.61	0.1
CSIS	0.099	0.14	62	73	81	84	1	3.5	0	0	0	0.65	0.1
BSHL	0.1	0.2	50	69	79	84	0	3	0.02	50	125	0.61	0.1
FPLT	0.099	0.1	64	75	83	86	0	4	0.001	40	150	0.45	0.1
DRGL	0.099	0.15	48	66	75	80	0	2	0	0	0	0.33	0.1
ABEN	0.05	0.14	63	73	78	82	0	0	0	0	0	0.65	0.1
FUMN	0.1	0.2	30	55	70	77	0	5	0.05	99	410	0.65	0.1
FMNT	0.1	0.2	30	52	66	73	0	5.5	0.05	99	460	0.65	0.1
FSMN	0.1	0.18	30	52	66	73	0	5.5	0.05	99	580	0.65	0.1
FLLD	0.1	0.18	30	55	70	77	0	5	0.05	99	420	0.65	0.1
FMSC	0.1	0.1	40	60	70	80	0	4.5	0.05	99	375	0.65	0.1
WDOP	0.1	0.1	54	69	78	82	0	3.5	0.05	99	120	0.61	0.1

For variable names and their explanation, we refer to (Arnold et al. 2011)

Appendix 2. Adjusting SWAT for leaf fall in the tropics

The dormancy and continuous leaf shed of the forests and woodlands of the Arc Mountains were represented in the model as follows. In the tropics, forests and woodlands do not have a dormancy period and they do not shed their leaves in winter; rather, during the dry period, they shed some of their leaves. Shedding leaves in SWAT depends on the day length (Neitsch et al. 2005). If the day length is less than the threshold day length, plants other than warm season annuals stop growing and come out of dormancy once the day length is greater than the threshold. For areas located between 20^{o} North and 20^{o} South, the threshold day length is given a value equal to the value of the shortest day in the region (Neitsch et al. 2005). Hence, there is no dormancy in areas located between 20^{o} North and 20^{o} South, which is the case for Tanzanian forests. However, the woodlands shed their leaves in response to water stress in the dry season and the forests keep their leaves all year except they continually lose a small proportion of leaves. This continuous loss contributes to the nutrient pool for the trees (Lundgren 1978).

To simulate this continuous shedding of leaves and seasonally increased leaf loss for the woodlands, a harvest operation (loss of leaves) is set up that starts at the beginning of the dry season (June) and continues till end of September. There is no automatic leave fall code included in the SWAT model. Thus, based on data from Lundgren (1978), the woodlands are assumed to be harvested (leaf fall) each month in the dry season. 95% of the biomass harvested (estimate of leaf fall) is assumed to be left on the ground to become a residue. The amount of biomass harvested is defined by the coefficient of harvest index. The harvest index for optimal growing conditions defines the fraction of the aboveground biomass that is removed in a harvest operation (Neitsch et al. 2005).

Appendix 3. SWAT Exceedance curves

Flow exceedance curve

The exceedance curve in Figure A3.1 supports the SWAT model fit for river flow. The comparison between the measured and the simulated exceedance shows that the model is relatively accurate in simulating low flows and high flows, except a slightly overestimation of flows in the range 10 – 20 mm.

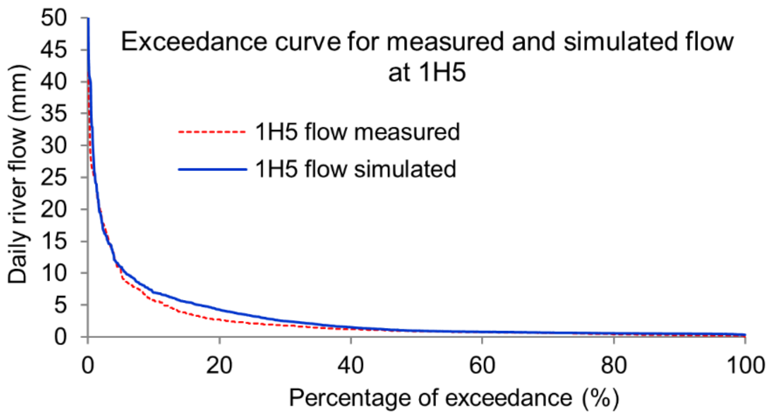

Figure A3.1: Exceedance curve for measure and simulated flow at 1H5

Number of days of pump failure at offtake point

The Upper Ruvu WTW offtake pumps located at Morogoro Bridge (1H8) frequently stops operating due to high sediment concentration at water take-off point in the Ruvu River. We know from personal contacts and experience that this phenomenon occurred several times in the past, but we are not aware of any reports on the number of days that the pumps were turned off due to high sediment concentrations. No information is available on the minimum sediment concentration that triggers the pump cut-off.

Therefore, a statistical approach was used in this study to estimate the minimum cut-off sediment level, and instead of a specific value a range of values were selected. This range, the percentage time that the pumps was turned off due to high sediment concentration was estimated using an exceedance curve show in Figure A3.2. Visual inspection of the exceedance curve, based on the understanding that the flatter the curve is the rarer the event, showed that the slope of the curve starts getting less steep around 2%, but it was not possible to identify a specific value. Hence, we took a range of values varying from 0.25% to 2.0 %, equivalent to one to seven days a year respectively, to represent the percentage of days that the pumps were turned off due to high sediment concertation in the river. We inferred the corresponding average daily sediment concentration levels that resulted in a frequency of pump cut-offs from the percentage exceedance curve (Figure A3.2) for the conservation scenario. Then, for the conversion scenario, we linked these sediment concentration levels to the exceedance percentages in Figure A3.3 and the corresponding number of days that the pumps fail in the Ruvu River. The number of days of cut-offs informed the estimation of the costs of failing to meet water demand on those days.

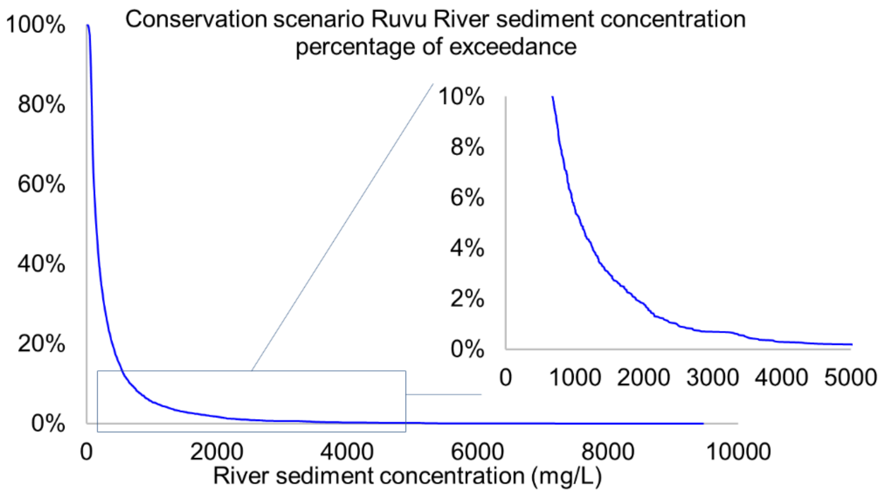

Figure A3.2: Percentage exceedance curve for sediment concentration at Morogoro Bridge in conservation scenario

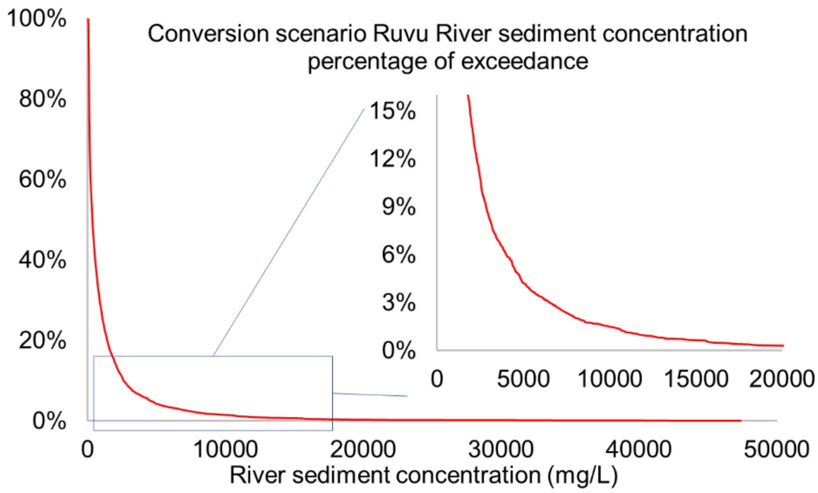

Figure A3.3: Percentage exceedance curve for sediment concentration at Morogoro Bridge in the conversion scenario

The results in Table A3.1 shows that the conversion scenario results in the total number of pump cut-off days varying from 20 to 56 days per year, depending on the cut-off sediment level.

Table A3.1 Equivalent cut off points to the selected % of pump failure times in the conservation scenario and identifying number of cut-off days in the conversion scenario based on cut-off points from the conservation scenario

Percentage of time that pumps stop due to high sediment concentration (conservation)	Equivalent number of days per year	Cut off point mg/L	Percentage of time that pump stop due to sediment cut-off point (Conversion)	Number of days per year
0.25%	0.9	4357	5.45%	19.9
0.50%	1.8	3495	6.85%	25
0.75%	2.7	2812	8.70%	31.8
1.00%	3.7	2491	10.05%	36.7
1.25%	4.6	2282	11.40%	41.6
1.50%	5.5	2106	12.20%	44.5
1.75%	6.4	2029	12.90%	47.1
2.00%	7.3	1885	13.89%	50.7

Appendix 4. Monetary valuation

4.1 Mindu reservoir siltation and costs of water supply to Morogoro

We used an exchange rate of TZS 2,138 to USD 1 in this paper (August 2015).

MOROWASA has estimated that increasing the dam height and constructing upstream check dams to regain design capacity (AAW 2012) will cost TZS 14 billion (appr. USD 6.55 million) (MOROWASA water engineer, pers comm, September 2015). Based on this cost figure, we estimated the cost of siltation per year by distributing the total cost due to siltation over the last 30 years.

We estimated the current average cost of siltation per year to be USD 218,273 (USD 6.55 /30 years), equivalent to an annual cost of USD 1.648/tonne of sediment (USD 218,273 / (4.3 tonnes/ha/yr * 30800 ha)).

The increase in sediment yield from the catchment of 6.07 tonnes/ha/yr leads to an increase in the annual cost of sedimentation by USD 308,103 /year (6.07 tonnes/ha/yr * 30800 ha * USD 1.648/tonne) due to the removal of forest and woodland from the Mindu catchment as in the conversion scenario.

4.2 Modelled length of water rationing periods in Dar es Salaam

Table A4.1 shows the number and duration of pump failure due to excess sedimentation under the conservation scenario; Table A4.2 shows the results of the same analysis for the conversion (forest loss) scenario. Comparison of the numbers in these tables reveals that under the conversion scenario, pump failure due to high sedimentation in the Ruvu River will not only lead to more frequent but also longer periods of tap water restrictions in Dar es Salaam.

Table A4.1 Mean number of cut-off events under the conservation scenario at different cut-off levels

Consecutive Cut-off days	4357 mg/L	3495 mg/L	2812 mg/L	2491 mg/L	2282 mg/L	2106 mg/L	2029 mg/L	1885 mg/L
1	0.9	1.3	2.1	2.0	2.8	3.0	3.4	3.6
2		0.2	0.3	0.4	0.5	0.7	0.8	1.0
3				0.2	0.1	0.1	0.2	0.2
4					0.1	0.2	0.2	0.1
5								0.1

Table A4.2 Mean number of cut-off events per year under conversion scenario at different cut-off levels

Consecutive Cut-off days	4357 mg/L	3495 mg/L	2812 mg/L	2491 mg/L	2282 mg/L	2106 mg/L	2029 mg/L	1885 mg/L
1	9.5	11.3	13.2	13.2	13.4	13.9	13.9	13.5
2	2.6	3.1	3.3	4.2	4.6	4.7	5.2	5.9
3	0.8	1.2	1.9	2.5	3	2.9	2.5	2.6
4	0.4	0.4	0.4	0.7	1	1.4	1.6	1.5
5	0	0.1	0.4	0.3	0.5	0.7	0.9	1
6	0.2	0.3	0.1	0.2	0.1	0.1	0.1	0.2
7			0.3	0.3	0.3	0.3	0.3	4
8					0.1	0.1	0	1
9							0.2	0.2

4.3 Substitution options and costs

Richer households tend to rely more on protected reservoirs, vendors who come to their door with pushcarts, or they buy in bulk from tanker trucks (Bayliss and Tukai 2011, Rostapshova et al. 2014). Some rich households have invested in private water storage, e.g. underground water reservoirs or water tanks on top of roofs, which gives them some buffer to cope with the lack of water supply (*ibid.*). Bottled water is also increasingly used as drinking water.

We developed a set of substitution rules for the volume of piped water used per capita, depending on the number of consecutive days of pump failure (see Table A4.3). This reflects substitution of potable water, assuming that people will opt for another piped water source, brought in from other supply areas via vendors with pushcarts or trucks. We assumed that some households who depend on taps from neighbours would go for more expensive bottled water to avoid queues at the water kiosks after two days of pump failure.

Table A4.3 Rule based assumptions for substitution of piped water in Upper Ruvu supply area

Source	Piped water use (l/capita/day)	Substitutes 1 day pump failure	Substitutes 2 days pump failure	Substitutes 3+ days pump failure
Tap at home	40	Buffer	Pushcart (35L) Bottled (5L)	Tanker (10L) Pushcart (15L) Bottled (5L)
Tap from neighbours	25	Kiosk (15L) Pushcart (10L)	Kiosk (10L) Pushcart (15L)	Kiosk (10L) Pushcart (10L) Bottled (5L)
Kiosk, pushcart vendor	25	Kiosk (15L) Pushcart (10L)	Kiosk (15L) Pushcart (10L)	Kiosk (15L) Pushcart (10L)

Substitution costs

In a small survey conducted in April 2015, we collected additional primary data on substitute costs in Dar es Salaam which consist of three Districts i.e. Administrative areas. We aimed to interview at least 30 respondents for each water vendor type. In each of the three Districts and with the help of Area Executive Officer we identified water vendor types. Subsequently, using non-random sampling procedures we selected at least 10 respondents for each water vendor type for interviews. Accordingly, we interviewed 10, 43 and 11 water vendors from Ilala, Kinondoni and Temeke Districts making a total of 64 respondents. These included 36 kiosk, 22 pushcart, and six truck interviewed water vendors. The survey aimed to generate price information for different water sources, during dry and wet seasons, and during water rationed and non-rationed periods. Main water sources or suppliers in Dar es Salaam are water kiosk, pushcart and truck who sell water directly to consumers both during wet and dry seasons as well as during water and non-water rationing time. Therefore, respondents were asked to express water price during wet and dry season. Similarly, respondents we asked to specify whether there was water rationing or either during a given season.

We used data from the literature (Kjellén 2006, Mwakalila 2007) and our primary data to estimate the increased costs of water faced by households' dependent on the Upper Ruvu for domestic water. In addition, we used the relative prices between tap water and neighbour water of Kjellén (2006) to infer a price for piped water bought from neighbours for 2015, for which we could not obtain prices, as well as prices from the DAWASCO website for official domestic, kiosk and tanker truck prices. The results presented in Table A4.4 show that prices vary across type of vendors, water sources and between rationed and non-rationed days. Prices vary across sources with the cheapest option being tap water.

Our price data for kiosks and pushcarts selling DAWASCO surface water during rationed periods shows that prices increase significantly when tap water is cut off or rationed. This is in line with a news article from IPS (2009) which suggests that prices from vendors increase from TZS 13.75 per litre to TZS 20 per litre when there are water shortages. The report by (Uwasi 2010) would suggest that our figures for kiosks are conservative, suggesting that these are in reality much higher at TZS 107 per 20 litres, and TZS 68 per 10 litre jerrycans than the official TZS 20 per 20 litres. For trucks, we found a lower price during rationed times, but it is unclear if this is because of subsidies or a lack of sufficient observations. Our tanker prices are slightly higher than those of Bayliss and Tukai (2011), who find an average price of TZS 7-9 per litre.

Table A4.4 Prices in TZS per litre per source

Source		**Kjellen (2006), Mwakalila (2007)**	**(DAWASCO 2013)**	**Inferred**	**Authors' own data, 2015**		
					Mean	Non-rationed	Rationed
Tap at home		0.27	**0.87**				
Tap from neighbour		1		**3.22**			
Borehole (kiosk)					3.5		
Standpipe, kiosk (surface water)	Official:		1				
	Market:				17.9	**14.2**	**20.1**
Pushcarts		5.4			24.4	**17.6**	**29.5**
Tanker truck		6	1.19		13.2	**15**	**12.8**
Bottled		100		**500**			

Note: prices in bold are used in the cost estimation.

Net cost of removing forests

Finally, we used the data from Tables A4.1 and A4.2, together with the assumptions on per capita use, substitution behavior (Table A4.3), prices (Table A4.4) and affected population (Table 2), to estimate the annual net cost of increased sedimentation at a range of cut-off levels. The results are presented in Table 4.5. Without further information on practical cut-off levels of sedimentation used to operate the pumps of the Upper Ruvu WTW, it is impossible to provide a more precise estimate of the costs.

Table A4.5 Annual cost of cut-off events resulting from increased sedimentation in Upper Ruvu (conversion minus conservation scenario) in millions of TZS

Consecutive Cut-off days	**4357 mg/L**	**3495 mg/L**	**2812 mg/L**	**2491 mg/L**	**2282 mg/L**	**2106 mg/L**	**2029 mg/L**	**1885 mg/L**
1	2,634	3,124	3,492	3,645	3,492	3,553	3,492	3,185
2	2,501	2,590	2,501	3,126	3,662	3,841	4,466	4,198
3	1,373	3,203	5,491	6,178	6,635	6,407	5,491	5,491
4	2,031	1,523	2,539	5,078	7,109	9,140	10,663	10,156
5	-	508	2,031	1,523	3,047	3,554	3,554	6,093
6	1,295	1,942	647	1,295	647	1,295	647	1,295
7	-	-	2,360	1,574	2,360	2,360	2,360	3,147
8	-	-	-	926	926	-	926	1,852
9	-	-	-	-	-	1,066	1,066	2,131
Total cost (in million TZS)	9,834	12,891	19,062	23,344	27,879	31,216	32,667	37,550
Mean per capita costs (in TZS)	16,824	22,054	32,612	39,939	47,696	53,405	55,887	64,241