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

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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).

95   Morerver, forests and woodlands do not produce water *per se*, and so valuation of the total annual
96   volume of water supplied has very limited policy relevance for understanding forest-related water
97   services beneficial to people (Lele 2009). Valuing the cost or benefit of a *change* in a specific service
98   provision throughout the year resulting from a *change* in forest quality or quantity is a more useful
99   approach when aiming to value forest ecosystem services (Balmford et al. 2011, Daily et al. 2009).
100
101 Many previous studies, particularly in data-poor settings, have abstained from providing economic
102 values for water-related services, or from linking economic values to changes in land use and
103 subsequent forest functioning (Campbell and Tilley 2014, Maes et al. 2012, Terrado et al. 2014).
104 Existing monetary valuation evidence is limited; for example, the TEEB (The Economics of
105 Ecosystems and Biodiversity) valuation database (Van der Ploeg and De Groot 2010) provides only
106 eight references and ten value estimates from primary studies for water-related benefits provided
107 by tropical forests, of which none are from Africa. The value of landscape management for water
108 related ecosystem services is hard to determine because of the lack of understanding of the
109 dynamics of water ecosystems and interactions between land and water systems, and because the
110 preferred quantity and quality depend on water users and time of year, and crucially; more water is
111 not always better (Brauman 2015, Schaafsma et al. 2015).
112
113 The aim of this paper is to (a) assess to what extent the presence of forests and woodlands regulates
114 the availability of water throughout the year in two major African cities, and (b) provide an estimate
115 of the economic value of this regulation service. We tackled these aims by linking the outputs of the
116 process-based model, the Soil and Water Assessment Tool (SWAT), to an economic valuation of the
117 regulation service of woodland and forest ecosystems. Through a comparison of scenarios with and
118 without tree-dominated ecosystems, we provide estimates of the monetary value of water
119 regulation by forests and woodlands, and the distribution of benefits among different socio-
120 economic groups. We demonstrate that our methodology is applicable to data scarce areas with a
121 case study on the Ruvu catchment in Tanzania (Figure 1).

2. Case study area

123 World Bank urban development data show that the percentage of the population in Tanzania living
124 in cities increased from 22% in 2000 to 31% in 2014. Dar es Salaam, with a population approaching 5
125 million (> 3000 persons per km^2 (Office of the Chief Government Statistician 2013), is expected to
126 see a further 85% increase in population between 2010 and 2040. This will increase water demand in
127 a city where the water companies already struggle to meet the water required by the existing
128 population (Nganyanyuka et al. 2014, Reweta and Sampath 2000).
129
130 At the same time, the principal supplies of water to Dar es Salaam and Morogoro are at risk from
131 upstream deforestation (Ngana et al. 2010, Nobert and Skinner 2016). Dar es Salaam city (the
132 commercial capital and largest urban area in the country) and Morogoro town (the capital of
133 Morogoro region) depend mainly on the Ruvu River for their surface water supply (Yanda and
134 Munishi 2007). This river originates in the Uluguru Mountains, part of the Eastern Arc Mountains
135 (Figure 1) – a mountain chain of global significance for its exceptional concentrations of rare and
136 endemic plants and animals (Burgess et al. 2007, Rovero et al. 2014). Despite conservation efforts
137 over many years, the conversion of forests to farmland has continued to the point where less than
138 30% of the original forest extent remains (Hall et al. 2009, Newmark 2002, Platts et al. 2011). The
139 rate of forest loss has slowed in recent years, with almost no forest lost within reserves in the past
140 decade. However, the frontier of forest conversion has reached the reserve boundaries, and
141 woodlands – which are largely unprotected – continue to be rapidly converted to agriculture (Green
142 et al. 2013). More subtle degradation of both protected and unprotected forests from illegal timber
143 harvesting, charcoal production and firewood collection also continues to threaten biodiversity,
144 carbon sequestration and hydrological services.

146   The Ruvu catchment covers an area of 14,390 km² and lies mainly in Morogoro Region, with small
147   parts located in Pwani Region. Forest and woodland cover 35% of the catchment, while crops such
148   as maize, African beans, rice, sesame, pineapple and sisal cover 10% (Swetnam et al. 2011). The
149   remainder is mainly grassland and bushland. In the west of the catchment are the Uluguru
150   Mountains, covering 3057 km², of which 309 km² is moist tropical forest (Platts et al. 2011). The soils
151   in these mountains are mainly Luvisols with a sandy clay loam texture (Msanya et al. 2001), making
152   them highly susceptible to erosion (Kimaro et al. 2008).

153
154   Three major rivers flow into the main Ruvu River: the Mgeta River flowing from the south-west of
155   the catchment, the Upper Ruvu River flowing from the east side of the Uluguru Mountain, and the
156   Ngerengere River flowing from the westside of the Uluguru Mountains. The main Ruvu River in this
157   catchment is the principle source of fresh water to citizens of Dar es Salaam, and the Ngerengere
158   River to citizens of Morogoro via the Mindu Dam. These two rivers, the Ruvu and Ngerengere, are
159   the focus of this study.

160
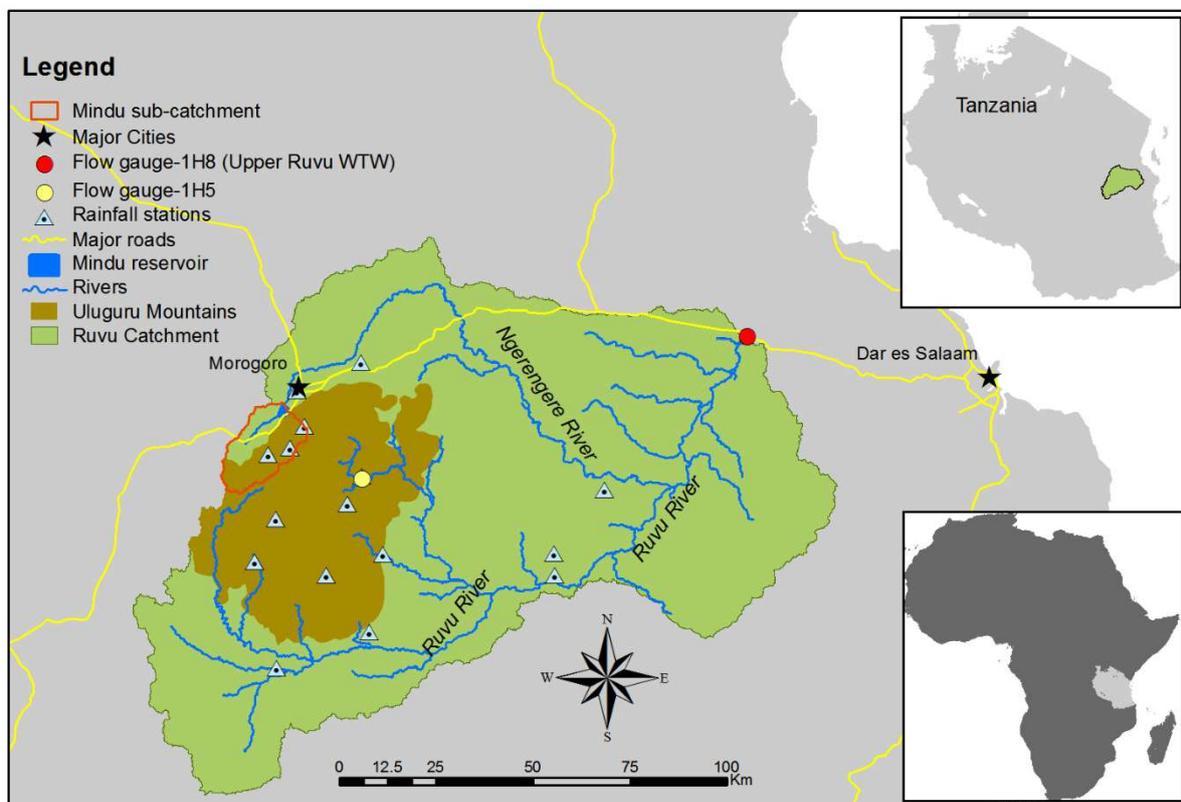
162   *Figure 1: Ruvu catchment map with important features (rivers, reservoir, important towns)*

163
164   In the 2000s it was estimated that 88% of the total water used in Dar es Salaam comes from the
165   Ruvu River, with the other 12% coming from groundwater sources (Kjellén 2006). Piped water for
166   Dar es Salaam came (and still comes) from three different water treatment works (WTW): Mtoni,
167   Upper Ruvu, and Lower Ruvu. Our analysis focuses on the Upper Ruvu WTW located in Mlandizi,
168   which receives its water only from the Ruvu River and is therefore fully and immediately dependent
169   on the Uluguru Mountains area and its forest and woodland. The impact of deforestation on the
170   Lower Ruvu WTW is not assessed in this study due to insufficient river flow data for model
171   calibration and validation at the Lower Ruvu WTW water off-take point. Mtoni WTW is not assessed
172   in this study, because its source location, the Kzinga river, lies outside the Ruvu catchment, and its
173   contribution, 9,000 m³/day, is much lower than the Upper Ruvu WTW with 80,000 m³/day (Kjellén

174 2006). Our study uses landcover change information and these water distribution figures in the
175 2000s. The potential increase of water treatment costs due to erosion caused by upstream changes
176 in land cover are beyond the scope of this study, as we do not have sufficient information to assess
177 the treatment process, such as the use of polymers or alum used to remove suspended solids, or
178 time series data of suspended solids (Cunha et al. 2016, Holmes 1988, Sthiannopkao et al. 2007,
179 Spellman 2008, Vogl et al. 2017).
180
181 At the Morogoro Bridge, along the Dar es Salaam-Morogoro road (1H8, see Figure 1), water from the
182 Ruvu River is pumped to the Upper Ruvu WTW and then conveyed to the Kimara reservoirs. The
183 design treatment capacity of the Upper Ruvu WTW was 82,000 m^3/day (Kjellén 2006). However, the
184 WTW was often unable to operate at full capacity, primarily because siltation of the Ruvu River
185 caused pump failure, leading to regular water restrictions or rationing in Dar es Salaam (Gondwe
186 2000, Kjellén 2006). Past maintenance work commissioned to solve siltation problems was not
187 successful (Gondwe 2000), including the Tanzanian Shillings (TZS) 300 million (USD 140 thousand)
188 spent to replace existing pumps (Africa Time 2015)[1]. Moreover, water supply from the rivers was
189 frequently insufficient. As a result, the Kimara reservoirs, with a total capacity of 34,200 m^3, were
190 never full and often ran dry after the morning peak demand (Kjellén 2006). Illegal abstraction and
191 leakage due to excess pressure within the distribution system were very common: of the total inflow
192 at the pump, 47% was estimated to be either wasted, used illegally (primarily for agriculture) or lost
193 at off-takes. In addition, an estimated 8% of the total inflow was leaked along the transmission line
194 between the WTW and the reservoirs, and 14% fulfilled the legitimate demand for towns and
195 villages along the transmission (Kjellén 2006). Only an estimated 32% of the potentially treated
196 water, i.e. 26,240 m^3/day at full capacity, reached the service reservoir.
197
197 The Ngerengere River, which flows into the Ruvu River, supplies water to Morogoro via the Mindu
198 Dam and reservoir. The Mindu Reservoir is located about 10 km south-west of Morogoro town. The
199 main source of water to the Mindu Reservoir are the seasonal and perennial streams flowing from
200 the forest and woodland reserve of the Uluguru Mountains situated at the eastern side of the
201 reservoir (Ngonyani and Nkotagu 2007).
202
203 The Mindu reservoir supplies 80-85% of the water for Morogoro town, equivalent to 6,927,000
204 m^3/year, but this is only sufficient to meet 64% of the total water demand (MORUWSA 2009). The
205 dam was constructed in 1983 (JICA 2013). However, within the last 30 years, the reservoir has lost
206 22% of its capacity due to siltation (AAW 2012). There have been no siltation removal operations
207 since the dam was built (AAW 2012). Although the consultancy report (AAW 2012) also suggested
208 various feasible dredging options, the Morogoro Urban Water and Sewerage Authority
209 (MORUWASA) chose to raise the dam height by 2.5 m (MORUWASA 2017). Therefore, we analysed
210 the cost of siltation based on the authority's strategy.

3. Methodology

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

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

221 agricultural expansion all forests and woodlands in the Ruvu catchment are converted to cropland
222 (maize and beans). The second is a 'conservation' scenario, where forest and woodland cover in the
223 Ruvu catchment is assumed to remain at the same level as in the year 2000. By comparing the
224 results of these scenarios, we quantified the role of woody habitats in the regulation of hydrological
225 flow and sediment control, and their impact on domestic water supply to urban residents of
226 Morogoro and Dar es Salaam.
227
228 As elsewhere in the Eastern Arc Mountains, woodlands in the Ruvu catchment are largely
229 unprotected, and the majority forests outside reserve boundaries have already been cleared (Green
230 et al. 2013). Our conversion scenario represents a case where funding is withdrawn, and conversion
231 continues into the Uluguru Nature Reserve, which contains most of the forest in the catchment
232 (Burgess et al. 2002), until all forests and woodlands are lost from the Ruvu catchment. In contrast,
233 the conservation scenario reflects that management of the Uluguru Nature Reserve is effective in
234 stopping conversion, and assumes similar levels of protection are extended to the woodlands.
235
236 We used SWAT to examine how changes in sedimentation affect the capacity of the Mindu Reservoir
237 and the functioning of the pumps supplying Dar es Salaam (see Section 3.2). For the assessment of
238 economic consequences in Dar es Salaam and Morogoro, we related sedimentation levels to the
239 resulting water supply problems (see Section 3.5).
240

3.2 Hydrological model

242 In this study, we chose to use the SWAT model to simulate the Mindu reservoir water level and its
243 sediment deposition, and the operations of the pumps that deliver water from the Ruvu River to the
244 Upper Ruvu WTW. We chose the SWAT model because of it flexibility, longevity and – crucially - its
245 capability to model sediment rates at daily time steps, which is necessary to assess the pump
246 shutdown events that depend on short-term sediment levels (rather than longer-term average water
247 quality indicators). SWAT is a freely available physical process-based model that can simulate
248 continuous-time catchment scale processes (Neitsch et al. 2011). Once the model is setup, different
249 management strategies and changes such as land use/cover can be assessed easily without excessive
250 investment of time and resources (Ashagre 2009, Baker and Miller 2013). Since the model is
251 integrated with a GIS interface it is convenient to analyse and present spatial variations (Easton et al.
252 2010).
253
254 SWAT addresses various water-related processes at watershed scale (Francesconi et al. 2016). It can
255 be used to identify runoff sources, areas of high soil loss, and the downstream consequences of the
256 land cover change. Its application has been successful at various temporal and spatial scales, in data-
257 scarce catchments, in both temperate and sub-tropical catchments. Although the model can be data
258 demanding, it has been used in data scarce areas with satisfactory accuracy (Betrie et al. 2011,
259 Ndomba et al. 2008, Nyeko 2015). Several studies have used SWAT to quantify provisioning and
260 regulating services, but very few peer-reviewed publications have used SWAT for valuing ecosystem
261 services (Francesconi et al. 2016), let alone in a Sub-Saharan context (Vogl et al. 2017). SWAT has
262 been applied in Tanzania to assess the impact of land management practices and land cover changes
263 on the watershed water balance (Ashagre et al. 2014, Dessu and Melesse 2013, Mango et al. 2011,
264 Natkhin et al. 2015, Ndomba et al. 2008, Notter et al. 2012, van Griensven et al. 2013, Wambura et
265 al. 2015), but never in combination with valuation.
266
267 Applying a process-based hydrological modelling tool, such as SWAT, in data-scarce catchments is a
268 challenge (Baker and Miller 2013, Dile and Srinivasan 2014, Ndomba et al. 2008, Nyeko 2015),
269 mainly due to the need for detailed model parameters and input variables such as rainfall, solar
270 radiation, plant growth, leaf area index, local soils, representative soil profiles, hydraulic properties
271 of soils, soil erodibility factors, land-use, irrigation management, crop management, and water

272   abstraction. Because of the non-linear nature of hydrological processes and the uncertainties in
273   measured parameters, it is important to evaluate model performance against measured data,
274   commonly done by using river flow and sediment load in rivers. However, these data are scarce in
275   catchments like the Ruvu, and due to infrequent maintenance of the few guaging stations, the
276   measured data can show significant error. In this study, we used various techniques to fill gaps and
277   reduce uncertainty in measured data. For example, we used literature to develop a crop database
278   for plants that are not listed in the original SWAT database (See Appendix 1, Table A1.3), and we
279   adapted the SWAT model to account for leaf shed in the dry season of forests and woodlands in the
280   catchment. This leaf fall contributes to the nutrient pool and allows for forest growth (see Appendix
281   2). We incorporated these modifications into a freely available version of the SWAT model
282   (http://swat.tamu.edu/).
283
284   In the model development, we assimilated rainfall data from 19 stations but only data from 16
285   stations were suitable for use in setting up the model. Out of the 16 stations only seven have reliable
286   data for the period 1995 – 2004, with some gaps. The rainfall datasets from the other nine stations
287   either have no data for the period 1995 – 2004 or have several days of missing data points. Most
288   climate stations fell apart in the early 1990s after the economy collapse in 1980 and have not been
289   restored since. We filled these data gaps using the WXGEN weather generator model (Williams and
290   Singh 1995) by using the strong historical dataset before 1995 (see Appendix 1 – rainfall data). We
291   adopted the land cover map from Swetnam et al. (2011) which is based on a 2000 land cover map
292   with some updates. For soils, we georeferenced the map of Hathout (1983) (see Appendix 1, Figures
293   A1.1 and A1.2), which identifies 16 major soil types in the catchment, based on texture and the
294   number of soil layers. We took representative soil profiles, for each soil type, from (Kimaro et al.
295   2001, Mbogoni et al. 2005, Msanya et al. 2001, Spooner and Jenkin 1966). Other data included soil
296   depth and other soil hydrological properties, agricultural management practices and water
297   extraction – for further details, see Ashagre (2009) and Easton et al. (2010).
298
299   The SWAT model uses the Modified Universal Soil Loss Equation (MUSLE) to calculate daily surface
300   soil erosion and sediment concentration in the streams (Neitsch et al. 2011). Due to the scarcity of
301   data on sediment concentration or total suspended load, we used turbidity as a proxy measure in
302   this study. Based on correlation estimates from Grayson et al. (1996) for a comparable catchment,
303   we estimated the suspended soil to be a factor 0.9 of turbidity for values lower than 1000 NTU
304   (Nephelometric Turbidity Units); for turbidity values higher than 1000 NTU, total suspended solid is
305   about 2.7 times the turbidity.
306

3.3 SWAT calibration and validation

308   We calibrated SWAT using daily rainfall data from the 16 weather stations spanning the years 1995 –
309   2000 with a model warming-up period of five years, 1990 - 1995. We calibrated the model for flow
310   estimation mainly using flow data from two points: Kibungo (gauge 1H5) and Morogoro Bridge (1H8,
311   see Figure 1). The intake point at Morogoro Road Bridge (1H8) is the outlet of the Ruvu catchment in
312   this study. It was not possible to use statistical tests to assess model performance at the catchment
313   outlet, 1H8, due to insufficient data points within the calibration and validation period. Instead, we
314   used the flow point at 1H5, which is a sub-basin outlet on the Uluguru Mountains, to test the model
315   accuracy during the calibration process using three goodness-of-fit recommended by Moriasi et al.
316   (2007): the model R^2, the percentage bias (PBIAS) of -11.8% and the Nash-Sutcliffe Coefficient (NSE).
317   The NSE has a value of 1 for perfect model fit, 0-1 when the model is better than taking an average
318   value, and <0 for very low model fit (Coffey et al. 2004). We transferred the calibrated parameters
319   over the whole catchment and used the available data at 1H8 to fine-tune the model by using a
320   visual/graphical approach. Although parameter transfer can reduce model performance, previous
321   applications of SWAT have shown that transferring parameter values within the catchment performs
322   reasonably well (Heuvelmans et al. 2004, Huisman et al. 2003). We validated the model using flow

323   data at 1H5 for the period of four years, 2001-2004, the details of which we discuss in the Results
324   section.
325
326   We further calibrated the SWAT model for sediment concentration in the streams by comparing the
327   modelled river sediment concentration to the sediment concentration estimated using the turbidity
328   data at 1H8 from Lopa et al. (2012). Additionally, we calibrated the model for sediment load and
329   reservoir volume at the Mindu dam, using information on dam capacity, operation and loss of
330   capacity due to siltation. We could not validate the model for its accuracy in simulating sediment
331   concentration in the Ruvu River, because daily sediment data or turbidity data for the validation
332   period were unavailable.
333

3.4 Scenario analysis

334
335   Both scenarios assume the same rainfall and climatic conditions that are measured and used for the
336   model calibration period, 1995 – 2000. Comparing the scenario results thus indicates how flow and
337   sediment concentrations would be altered if the forests and woodlands in the Ruvu catchment were
338   replaced with the two most dominant crops: maize and beans (Green et al. 2013). We ran the two
339   scenarios at a catchment scale and analysed them at catchment and sub-basin scale where the
340   Mindu Reservoir is located.
341
342   For Morogoro, in the absence of measured records of the outflow from the Mindu reservoir, we
343   estimated the outflow in the SWAT model by using a storage target: the principal volume of the
344   reservoir. We simplified the spill control from the dam reservoir and assumed that any water coming
345   into the reservoir above this volume overflows to downstream areas (this has no material impact on
346   our results). No measures are taken in the scenarios to reduce sedimentation in the Mindu reservoir,
347   so that soil erosion-induced sedimentation results in the reduction of reservoir capacity.
348
349   For Dar es Salaam, we based the analysis of the value of water-regulation services provided by
350   forests and woodlands of the Ruvu catchment on the incidence of pump failure due to
351   sedimentation at the Upper Ruvu WTW offtake point at Morogoro Bridge (1H8) in the two scenarios.
352   It has been reported on several occasions that the Upper Ruvu WTW offtake-pumps, located at
353   Morogoro Bridge (1H8), have stopped operating due to the high concentration of sediment in the
354   river. The Dar es Salaam Water and Sewerage Corporation (DAWASCO) were said to switch off their
355   pumps at NTU values above 1500, sometimes multiple times per day (M. Cadman, pers. comm.), but
356   we could not corroborate this information with DAWASCO documentation. This NTU level is well
357   above safety standards for drinking water quality (<5 NTU) and turbidity levels that can cause pump
358   problems >10NTU (Uhrich and Bragg 2003). Data on the number of days and hours that the pumps
359   have been turned off due to sediment problems were unavailable. Therefore, we used the slope of
360   the exceedance curve of the conversion scenario to determine the minimum sediment
361   concentration in the river that causes pump failure or deliberate cut-off to protect pumps from
362   failure (see Appendix 3). The range of interest is below this maximum percentage, where the
363   exceedance curve is gradual and sediment concentrations are high. For this range, where a major
364   increase in sediment concentration leads to a small increase in the probability of sediment
365   exceedance, we estimated the frequency and costs of pump cut-off under both scenarios.
366

3.5 Monetary valuation

367
368   A range of valuation methods is available for valuing (urban) ecosystem services, and avoided
369   expenditure and replacement cost methods are most often used for regulation services (Gómez-
370   Baggethun et al. 2013). We adopted cost-based approaches to value the changes in water supply to
371   Morogoro and Dar es Salaam. Benefit transfer was impossible, because relevant studies on the
372   monetary value for water-related benefits provided by tropical forests were unavailable. Specific
373   studies or data for Tanzania on the costs of damages to approximate the value of supply changes,

374 such as health problems or time lost to increased water collection time were unavailable. The
375 budget of the study was too limited to collect primary data with methods requiring large samples.
376
377 We therefore adopted a cost-based valuation approach to relate the annual sedimentation of the
378 Mindu reservoir to the (avoided) costs of increasing the Mindu Dam height to maintain the reservoir
379 capacity, and thereby the water supply to Morogoro, using information from a recent consultancy
380 report on the dam (AAW 2012).
381
382 For the valuation of impacts on the water supply to Dar as Salaam, we used market pricing and
383 substitute cost methods and developed a set of rule-based assumptions based on existing studies of
384 the water market in the city, as presented in Section 4.4. The main price information for substitute
385 water sources was obtained from secondary data: public websites, the DAWASCO website, and
386 published reports (see Table A3.3). In a small survey, we collected additional primary data on
387 substitute costs in three districts of Dar es Salaam in April 2015 (see Appendix 4). We interviewed 36
388 kiosks, 22 pushcart vendors, and six trucks to obtain price information for different water sources,
389 during dry and wet seasons, and during water rationed and non-rationed periods.

4. Results and discussion

4.1 Model Accuracy

392 The SWAT model achieved good agreement between measured (dark blue) and simulated (light
393 blue) river flows at 1H5 and 1H8, except for over-estimation of the base flow in some years (Figure
394 2ab). The model accuracy in the calibration process, simulating flow at 1H5 as compared to the
395 measured flow, had a coefficient of determination (R^2) of 0.45, an NSE of 0.25, and a PBIAS of -
396 11.8%.
397
398 We used the estimated sediment concentration from measured turbidity data (panel c in Figure 2),
399 which exhibited considerable uncertainty, to guide the sediment calibration process. When the
400 measured data exhibit significant uncertainty, calibration of models using goodness-to-fit measures
401 can misinform the modeller. Hence, we use the sediment data derived from turbidity data only for
402 guidance purposes. With the current parameters set, comparing model outputs with measured data
403 (turbidity) showed that the model did not overestimate the sediment concentration in the river,
404 suggesting that our estimates of soil loss were conservative, and the model fit for purpose. The
405 calibrated model showed that highest soil erosion occurs in November to January (see Figure 2c).
406 Sediment load is high from September to December, even though rainfall is highest in March and
407 April, probably because the higher vegetation cover in the March to May period reduces surface
408 runoff and subsequent soil erosion. Later in the year (September to December), following the long
409 dry season (June to September/October), the ground is bare and moderate rainfall can cause
410 significant erosion, especially in areas that are burnt in preparation for the planting season
411 (Heckmann 2014, Itani 1998, Kato 2001).
412
413 During the calibration period, in terms of stream flow simulation, the model slightly but consistently
414 overestimated the flow rate during the dry season, which resulted in a low NSE value and a negative
415 PBIAS. The R^2 was high showing a good collinearity between the simulated and the measured data.
416 Based on suggested model performance grade by Moriasi et al. (2007), the model performed almost
417 satisfactory according to the R^2 and NSE, and satisfactory based on the PBIAS. The model did neither
418 overestimate flow nor sediment. The conservative model results during the high flow season are
419 important for the use of sediment concentration outcomes as the determining factor for pump
420 shutdown at the WTW.

419 The model validation, run for the period 2001 – 2004, resulted in a similar model accuracy to that of
420 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.
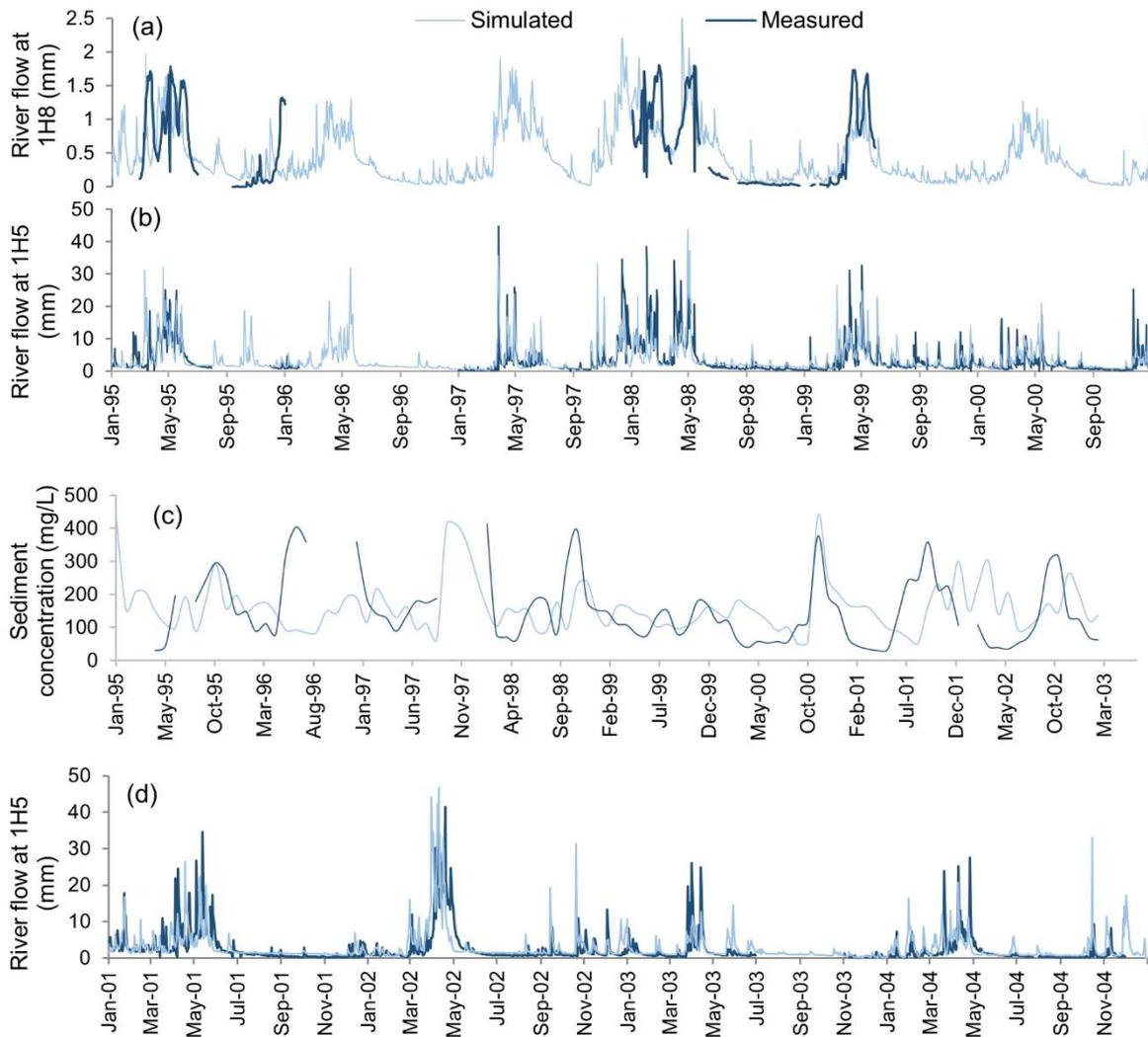
Figure 2: a) Daily measured (dark blue lines) and simulated (light blue lines) flow of Ruvu River at Morogoro Bridge during calibration (1H8); b) Daily measured and simulated flow of Ruvu River at Kibungu (1H5) during calibration; c) Monthly average simulated sediment concentration and the sediment concetration 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.
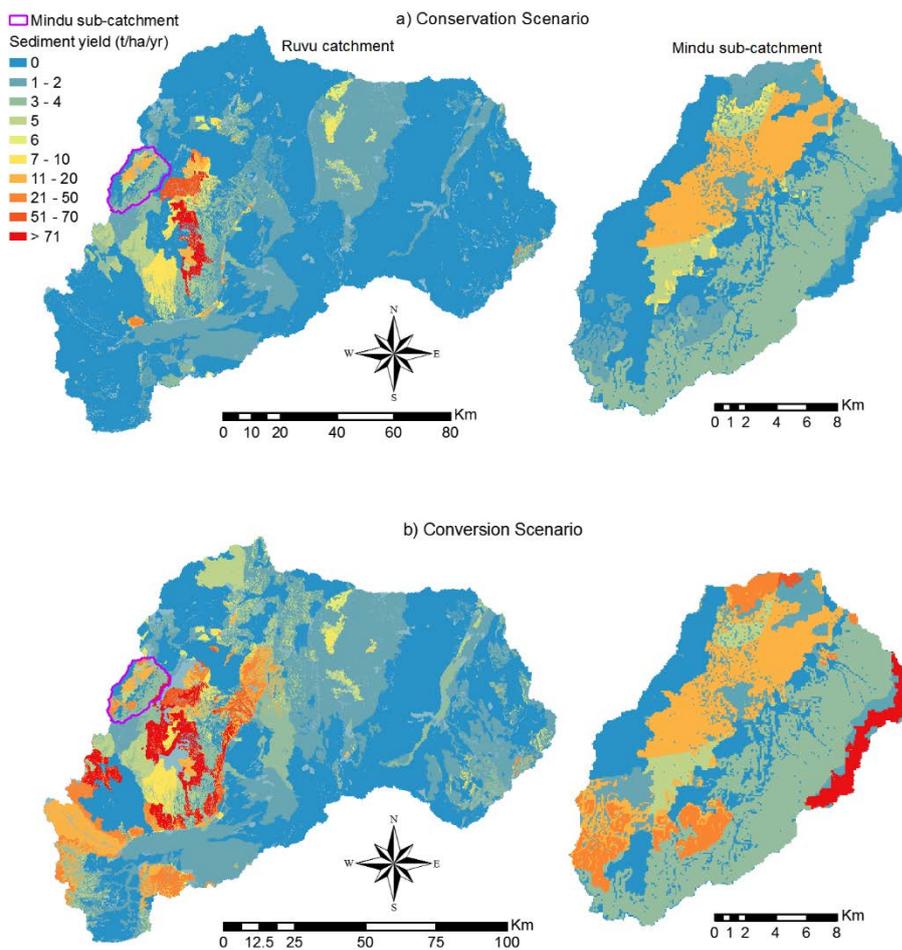
Figure 3: Comparison of rates and patterns of soil erosion under our conservation and conversion scenarios; a) soil erosion in Ruvu Catchment and Mindu Sub-catchment under the conservation scenario; b) soil erosion in Ruvu Catchment and Mindu sub-catchment under the conversion scenario.

4.3 Mindu reservoir siltation and costs of water supply to Morogoro

Annual sedimentation is estimated at 0.157 million m³/year and has reduced the capacity from 20.7 million m³ at design to 16.0 million m³ 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 m³ (1% of reservoir volume) in the conservation scenario to 0.280 million m³ (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.
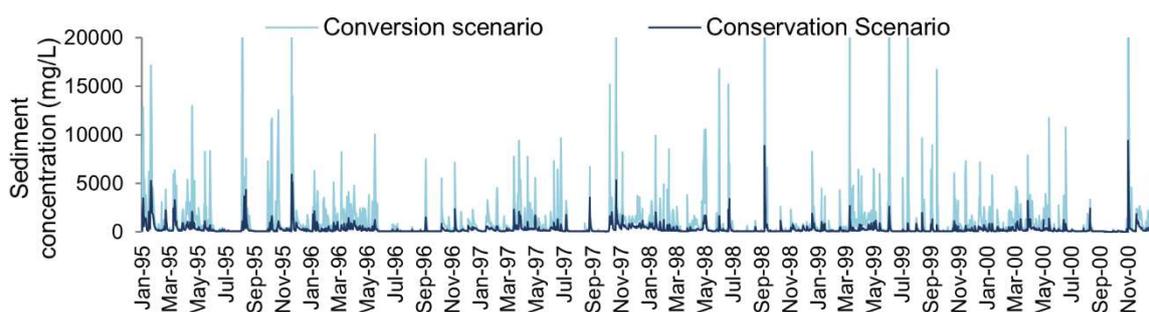
Figure 4: Sediment concentration at Morogoro Bridge (1H8) in conservation and conversion scenarios.

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

493 seven days of pump cut-off per year) is above the suggested operational pumping cut-off level of
494 1500 NTU. The SWAT sediment estimates for the conversion scenario in turn suggest that conversion
495 of the Ruvu catchment's forests and woodlands would cause tap water to be unavailable in Dar es
496 Salaam on 20 to 51 days each year (depending on the exact cut-off level, see final column of Table
497 1). Our results suggest that pump failure due to high sedimentation in the Ruvu River would not only
498 lead to more frequent but also longer periods of pump outage in Dar es Salaam (see Appendix 4,
499 Table A4.1 versus A4.2).
500
501 Table 1. Number of days of that pumps are stopped under conservation and conversion scenario for
502 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

503

4.4.2 Number of water consumers affected

504 Rates of household access to safe water sources in Dar es Salaam cannot be determined with
505 certainty (Bayliss and Tukai 2011); hence the volume of tap water used by households is unknown.
506 About 60% of the total demand for water in Dar es Salaam is domestic, 10% commercial, 10%
507 industrial and 20% institutional (WaterAid-Tanzania and Tearfund 2003). Although commercial,
508 industrial, and institutional demand is more likely to be fulfilled by tap water compared to domestic
509 use, we assumed that these percentages hold true for allocation of Upper Ruvu water. Hence, we
510 assumed that 60% of the 26,240 m^3/day that reaches the Kimara service reservoirs from Upper Ruvu
511 (Kjellén 2006), i.e. 15,744 m^3/day (15.7 million litres), is available for domestic use (see Table 2). This
512 assumption may overestimate the available water for domestic use as it ignores further leakage
513 from the distribution system (*ibid.*). Households that are supplied by the Upper Ruvu WTW are not
514 provided with tap water from other sources in the water distribution network, for example, from the
515 Lower Ruvu WTW (Bayliss and Tukai 2011). We hence assumed that stopping pumps results in an
516 immediate stop in the supply of piped water to the Upper Ruvu supply area. The storage capacity
517 reported by DAWASCO in 2012/13 was much lower than the demand, with a storage capacity
518 duration of just 3.4 hours; an Energy and Water Utilities Regulatory Authority report (EWURA 2013)
519 shows that there was hardly any buffer at all, which justified this assumption.
520
521 DAWASCO estimated that the average per capita consumption is 40 litres per day, which is expected
522 to apply to connected households (EWURA 2013). Tanzania's National Water Policy (2002) objective
523 is to ensure the provision of 25 litres of potable water per capita per day. Ease of access tends to
524 lead to higher per capita use of water among households with their own taps, compared with other
525 households. These figures are lower than of the total water use per household in Rostapshova et al.
526 (2014). The difference in water consumption lies mainly in drinking water use; for cooking, washing,
527 and cleaning non-piped sources are more prevalent among those without taps at home
528 (Rostapshova et al. 2014). We used these volumes per capita to estimate the number of households
529 that receive water from the Upper Ruvu: 40 litres for households with easy access via a tap, and 25
530 litres of piped water per day for other households, who buy DAWASCO water from their neighbours,
531

532 kiosks or vendors. We assumed that households use non-piped water to fulfil further non-drinking
533 water demand based on (Bayliss and Tukai 2011).

534

535 Around 62% of people in Dar es Salaam get their water from a tap (National Bureau of Statistics
536 2009), but only 8% have a tap at home. Others get piped water through neighbours (38%), or kiosks
537 or vendors (16%). These groups also tend to vary in wealth and substitution behaviour. Therefore,
538 we disaggregated the benefits of water supply by these groups in subsequent steps.

539

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

544

545 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*

546
547

548 *4.4.3 Substitution options and costs*
549 Because of frequent rationing of water in Dar es Salaam, households use multiple sources of water.
550 Alternative sources include groundwater, rainwater, surface water (streams, rivers) and water from
551 other areas brought in by water trucks. Access to one's own tap water is skewed towards the richer
552 population: only 3% of the poorest quintile are connected to a public network tap compared to 24%
553 of the wealthiest quintile, and 18% of the poorest quintile obtain drinking water mainly from
554 vendors (Rostapshova et al. 2014). Different groups opt for different substitutes. Water vendors are
555 the most used alternative (Nganyanyuka et al. 2014, Thompson et al. 2000), but richer households
556 sometimes buy in bulk from tanker trucks or use privately owned tanks or reservoirs (Bayliss and
557 Tukai 2011). Based on this information, we developed a set of rules for water substitution to
558 pushcarts, trucks or bottled water, depending on the source of piped water and the number of
559 consecutive days of pump failure (see Table A4.3). For households with taps at home, we assumed
560 that they would reduce their usage to 30 litres if water rationing lasted three or more days, but for
561 other groups we assumed that they would not cut back the volume used based on Rostapshova et al.
562 (2014) and Bayliss and Tukai (2011).

563

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

569

570 *4.4.4 Net costs of removing forest and woodland*
571 We used the price variation and substitution behaviour information to estimate the increase in
572 water costs incurred because of upstream loss of woody land covers. The estimated costs associated
573 with a normal, non-rationed day for people depending on the Upper Ruvu WTW for their piped
574 water are approximately TZS 90 million per day (USD 42 thousand), equivalent to ~ TZS 154 per
575 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

612 interlinked challenges of water provision, especially in countries that happen to be data-poor. Our
613 paper demonstrates a possible approach, but considerable uncertainties and challenges remain, as
614 we outline below.
615
616 First of all, in 2016 the water supply system for Dar es Salaam changed and new, larger pumps were
617 installed, but we could not incorporate this in the modelling because there are no comparable data
618 from the 2010-2016 period to enable this modification. Without any public information on the
619 sensitivity of the new pumps to sediment rates, we cannot tell whether our quantified outcomes for
620 Dar es Salaam still hold, but the qualitative findings would be expected to remain relevant and it
621 does not require altering our methodological approach. The modification of the system has no effect
622 on the value of water provision to Morogoro.
623
624 While we needed a tool like SWAT that can relate changes in land-use to downstream changes in
625 water quality and quantity at a fine spatial and temporal scale, such tools are often data demanding.
626 Due to data scarcity, of which most pressing are data for the hydrological model setup and
627 calibration, pump management in response to sedimentation, and substitution behaviour of tap
628 water users our methodological approach relied on a series of assumptions based on available
629 statistics and other evidence. We considered the SWAT model estimates of the suspended sediment
630 concentration sufficiently robust to use the outputs for value assessment. The model accuracy in the
631 simulation of sediment concentration and yield can be improved by monitoring sediment
632 concentration for an extended period, and estimation of a turbidity-to-sediment-concentration-
633 curve (Fisher et al. 2017). A recommendation following from our study would be to invest in data
634 monitoring. The SWAT model consistently over-estimated soil erosion for the month of January,
635 potentially because of the minimum assumed uniform USLE management factor, a model parameter
636 for soil conservation due to different practices or crop cover (Wischmeier 1979). Our estimated
637 mean soil loss rate in the Mindu Catchment of 4.43 tonnes/ha/yr on average is lower than the
638 average figure estimated in AAW (2012) of 6.5 tonnes/ha/yr. The lower soil loss estimation in the
639 model is mainly because our analysis only covers soil loss from surface erosion and excludes other
640 types of erosion, such as gully erosion, for which data were unavailable (Ashagre 2009). This means
641 that our ecosystem service estimates are probably conservative.
642
643 In addition, we did not consider climate change projections in the scenario analysis. Conway et al.
644 (2017) studied future climate and trends using 34 general circulation models. Two-thirds of these
645 models indicated more frequent extreme rainfall events in Tanzania, i.e. higher likelihood of intense
646 rainfall and prolonged dry spells. In addition, the model ensemble rainfall predictions by GLOWS-FIU
647 (2014) suggested that the existing seasonality in the Ruvu catchment will be preserved under future
648 climate scenarios with an increase in rainfall during March and April. Higher intensity rainfall is
649 usually associated with higher soil erosion and flooding (Arnaud et al. 2002, De Risi et al. 2018,
650 Römkens et al. 2002). Therefore, the impact of removing woody habitats from upstream catchments
651 could result in higher rates of soil loss and peak discharges than reported here. Similarly, the level of
652 water scarcity in this study could be under-estimated (climate projects suggests longer dry spells).
653 Hence, our conclusions regarding the value of forests and woodlands for water-related services
654 would likely be reinforced by considering future climate change scenarios.
655
656 Another challenge relates to linking hydrological models and economic valuation. We demonstrate
657 that to understand how forest and woodland cover changes affect the benefits of water-related
658 services, a comparison of two situations or scenarios with different land-use patterns and therefore
659 water quantity and quality is a useful and feasible approach. Data availability and budget limitations
660 meant that only a limited set of valuation methods was possible. Our estimates are probably
661 cautious because we did not assess the non-financial health costs of reduced water use or
662 substitution. Water consumers, especially poorer households who cannot afford to buy an equal

663 amount of water when prices increase under water shortages, may either have to resort to other
664 sources, often of lower quality, or buy less water; Bayliss and Tukai (2011) found that they opt to
665 spend more as they cannot cut down further. We did not include the costs of obtaining substitutes,
666 such as longer walking distances, or the health costs or using less or low-quality water, e.g. Collier et
667 al. (2012), Dupont and Jahan (2012), Zivin et al. (2011). In many of the informal settlements in Dar es
668 Salaam, piped water infrastructure is not available and these areas rely to a great extent on
669 groundwater resources (Bayliss and Tukai 2011). However, the groundwater table is decreasing, and
670 salinity due to increased industrial expansion and uncontrolled drilling is already a problem in
671 several areas (Meena and Sharif 2008, Mtoni et al. 2012, Van Camp et al. 2014). Due to salinization,
672 in combination with pit latrine contamination, the quality of both groundwater and vendor water is
673 not of safe standards (Kalugendo 2008). Our water valuation methodology ignores price elasticity
674 effects on water demand, but available elasticity estimates for other developing countries tend to
675 show that demand for domestic water demand, and especially for potable water, is inelastic, albeit
676 not perfectly (Nauges and Whittington 2010, Noll et al. 2000). However, any upward bias in our
677 value estimates from ignoring price elasticity of demand is expected to be offset by the substitution
678 cost components that we excluded. Furthermore, we did not include the impacts of changing water
679 flows on illegal users of Upper Ruvu water, water losses in the distribution system, impacts on
680 commercial, public and industrial sectors, and impacts on water use outside the urban areas,
681 including hydropower and irrigation. Costs associated with river water quality deterioration resulting
682 from deforestation were beyond the scope of this paper. Finally, impacts of deforestation on riverine
683 flooding in these cities have not been assessed, but they are known to occur and lead to casualties,
684 emergency displacements, and serious public health problems (De Risi et al. 2018, IFRC 2011).

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

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

710 Our study shows that sustainable management of catchment forests and woodlands, especially in
711 the mountains, is crucial for the health and wellbeing of people living downstream. Our integrated
712 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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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°51' S to 6°52' S and longitudes 37°30' E to 37°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.
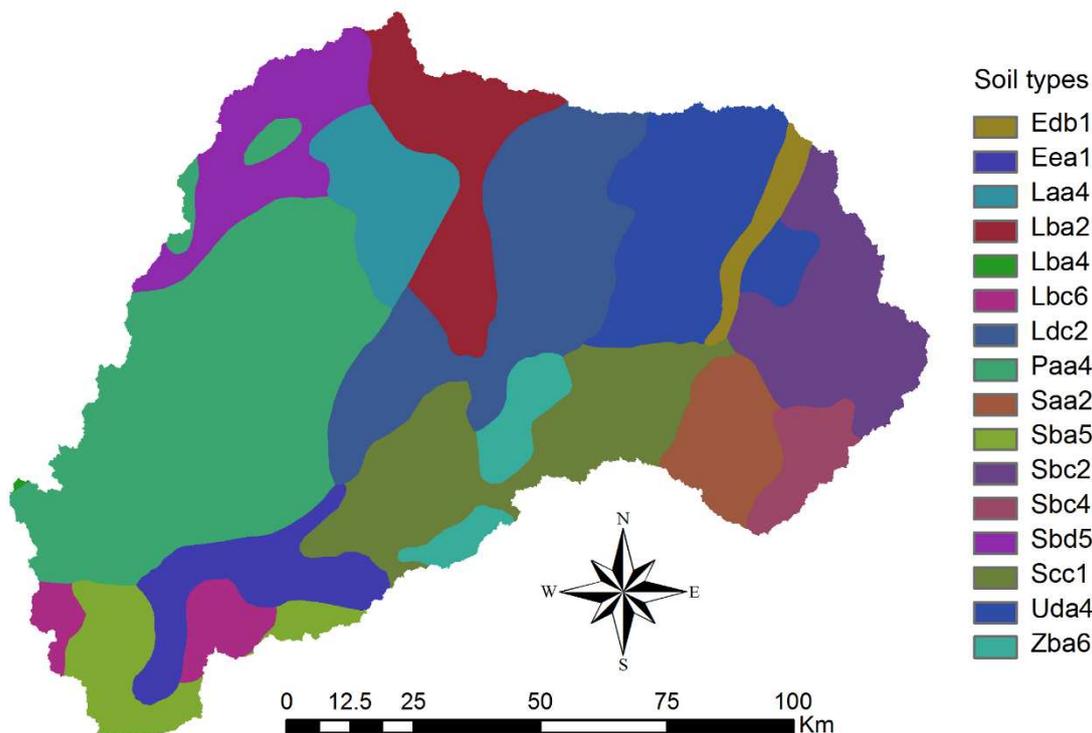
Figure A1.1: Soil map of the Ruvu catchment based on Hathout (1983)

29

1242   Table A1.1. Ruvu soil map and profile details based on Hathout (1983), Kimaro et al. (2001),
1243   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

1244   C=clay, S=sandy, and L=loamy - Based on Natural Resources Conservation Service (NRCS) soil classification
1245   Soil infiltration rate when thoroughly wet: A – high, B – moderate, C – slow, D – very slow
1246
1247

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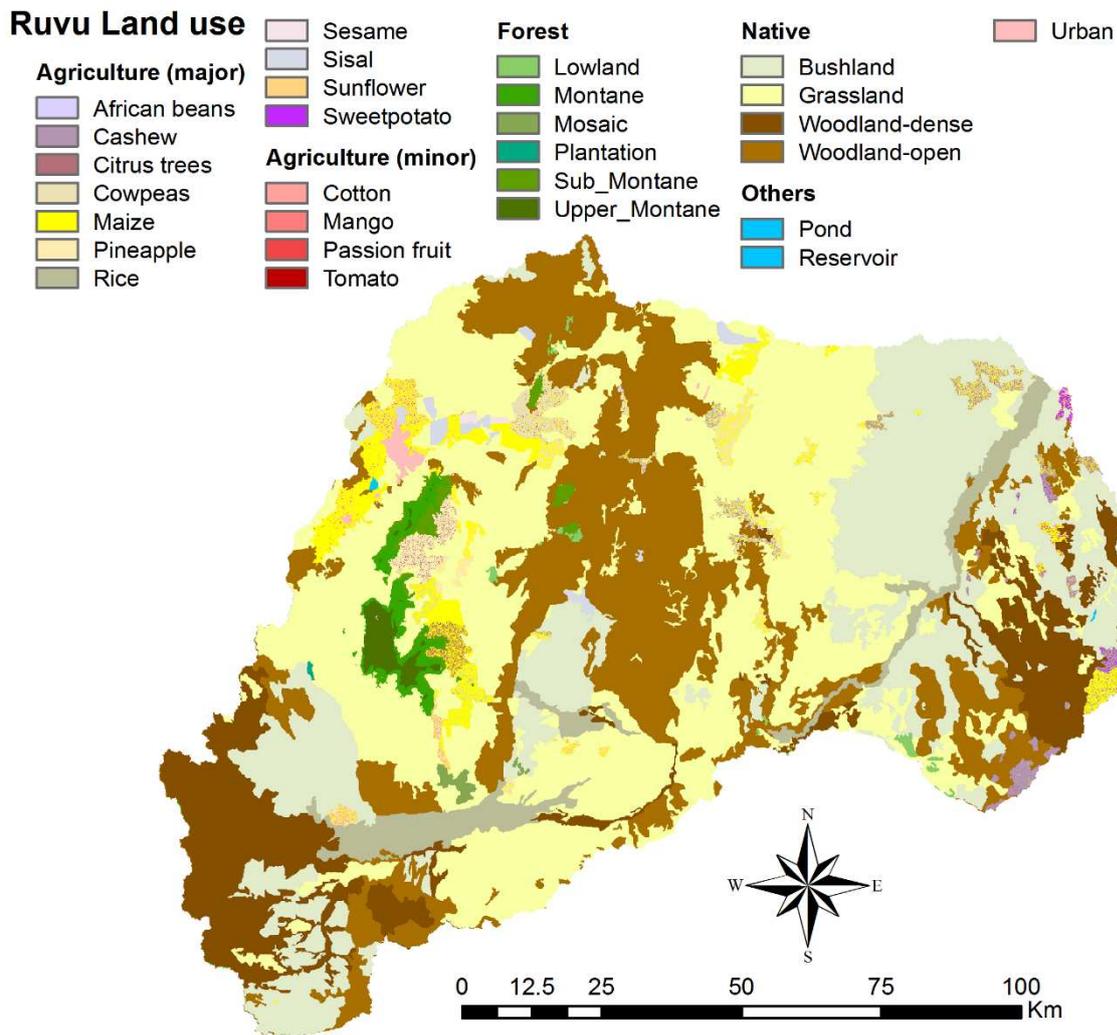
Figure A1.2: Land use map of the Ruvu catchment based on Swetnam et al. (2011).

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).

1269 We generated further daily climatic data using the WXGEN weather generator. The input for the
1270 WXGEN weather generator include average monthly precipitation, monthly maximum and minimum
1271 temperatures along with their standard deviations, and monthly precipitation with its standard
1272 deviation, skewness, wet day/dry day probabilities taken from the grid surface developed by Texas
1273 A&M University. The grid surface was developed using climate data from the World Meteorological
1274 Organization (WMO) database for Eastern Africa for the period of 1975 to 2001. These datasets were
1275 used to derive coefficients for parameterizing the WXGEN weather generator using the WXPARM
1276 program developed by TAMU Blacklands Research Centre (Sharpley and Williams 1990). The WXGEN
1277 coefficients were entered into the ANUSPLIN software to create gridded surfaces of each coefficient
1278 (Hutchinson 1999).
1279
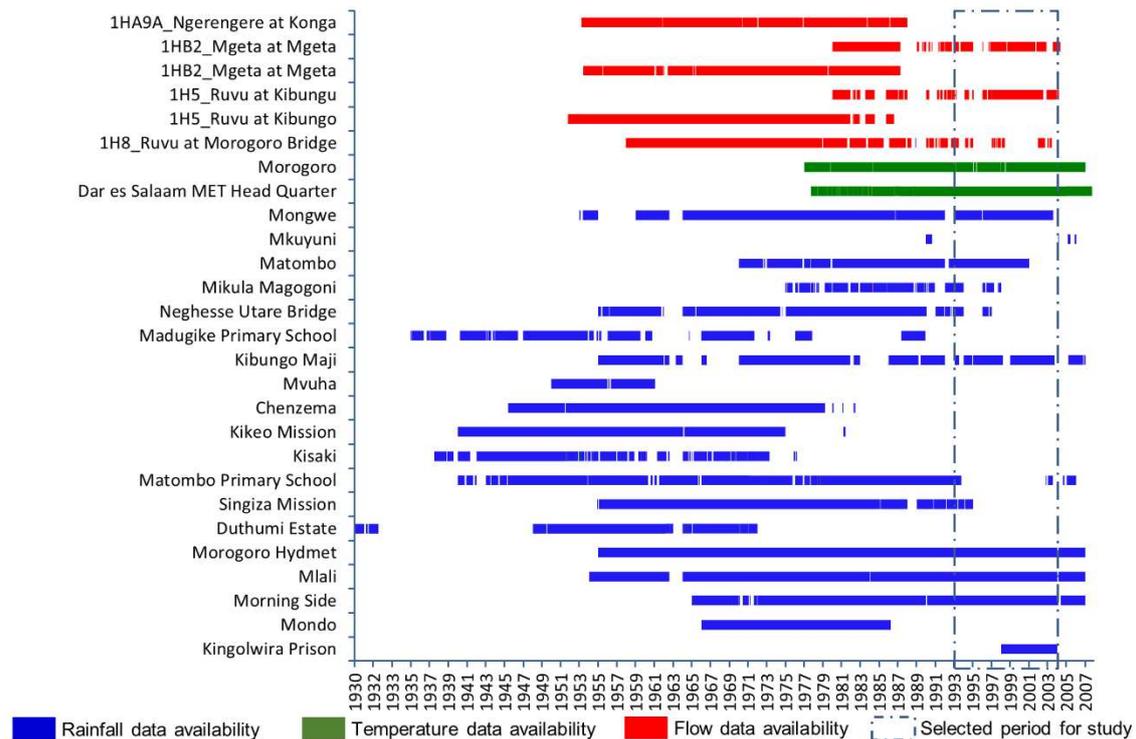
1280
1281 *Figure A1.3: Measured data availability for Ruvu Catchment*
1282
1283 Table A1.2. Rain fall stations used in SWAT model setup

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		

1284

32

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 20º North and 20º 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 20º North and 20º 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.
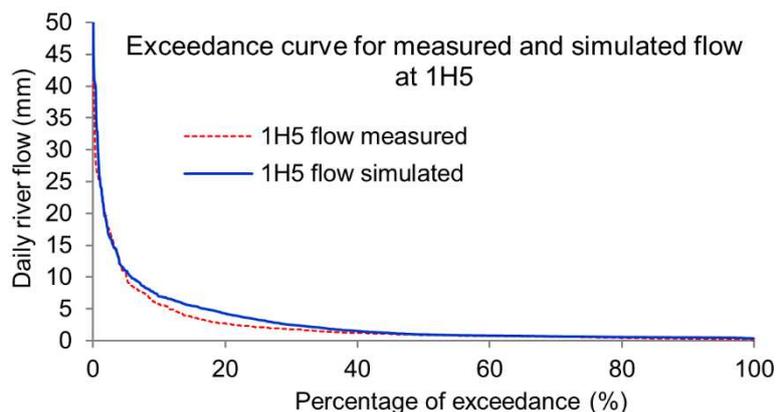
Figure A3.1: Exceedance curve for measure and simulated flow at 1H5

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.
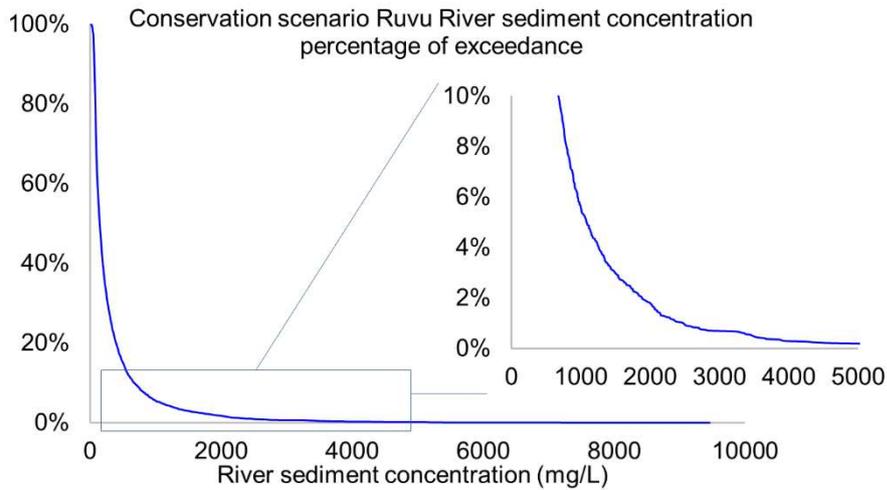
Figure A3.2: Percentage exceedance curve for sediment concentration at Morogoro Bridge in conservation scenario
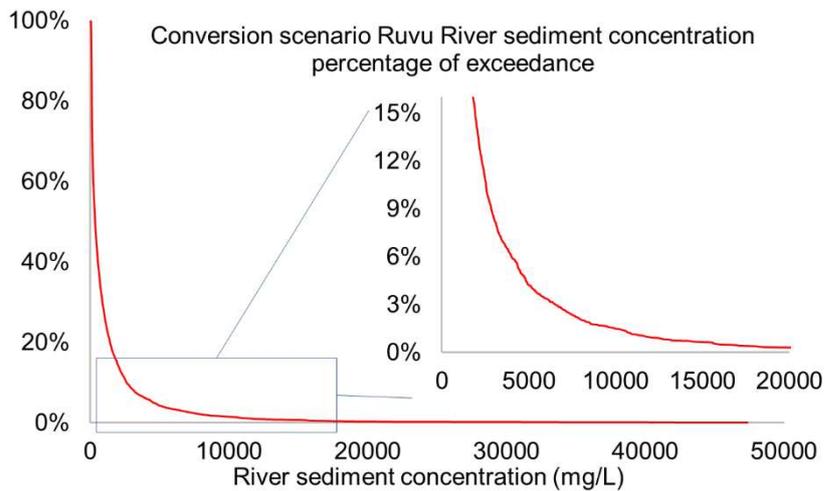
Figure A3.3: Percentage exceedance curve for sediment concentration at Morogoro Bridge in the conversion scenario

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