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Case study of Pangani Basin, Africa

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Multi-objective analysis of the green-blue water uses in a highly utilized basin. Case study of Pangani Basin, Africa

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ABSTRACT

The concept of integrated water resource management (IWRM) attempts to integrate all elements of water resources. Different tools are developed to assist in developing sound IWRM plans. One such tool is multi-objective analysis using integrated hydro-economic model (IHEM). However, IHEM mainly deals with the optimization of river flow (blue water) in a river basin. This paper linked a distributed model of green water (landscape water uses) in the upper catchment, with mainly blue water uses in the lower catchment of the Pangani Basin. The results show that agricultural water use has the highest water productivity and competes with all other objective functions in the catchment. The generation of firm energy competes with the downstream ecosystem requirements. The integrated study shows that improving rainfed cropping through supplementary irrigation has comparable marginal water values to full scale irrigation but are much higher compared to hydropower. However, hydropower has more benefits if used conjunctively with the environment. The methodological approach has increased the understanding of trade-offs between green – blue water uses that are highly interdependent in African landscapes.

Keywords: Multi-objective Optimization, Reservoir Operation, Hydrological Model, Pangani.

1. Introduction

Water forms the backbone for economic productivity and social wellbeing in many parts of the world, in particular in the semi-arid parts of Africa. With growing demands for water, it is becoming increasingly challenging to satisfy those needs (Gourbesville 2008; Komakech et al. 2012). Competition between different water uses and between upstream and downstream uses is therefore escalating (de Fraiture et al. 2008). Many river basins are overexploited, and the capacity to meet different social demands is decreasing (Molden et al. 2007).

In Africa, over 60% of the total population relies on water resources that are limited and highly variable (UNEP 2010). About 75% of the continent's cropland is located in arid and semi-arid areas, where irrigation can greatly improve productivity and reduce poverty (Smith 2004; Vörösmarty et al. 2005). Multipurpose dams have been developed in various river basins to provide economic benefits to water users. However, many such projects are failing to provide their expected benefits (WCD 2000; Ansar et al. 2014). Furthermore, dams often create large negative social and environmental externalities such as the displacement of communities and dis-benefits to downstream users (both communities and ecosystem) because of modified river hydrology (Malley et al. 2007).

According to Postel (1992), the main thrust of the management of river basins is finding ways of turning these potential conflicts into constructive cooperation, and to turn what is often perceived as a zero–sum predicament, in which one party's gain is another's loss, into a win–win proposition. River basin management should therefore aim to maximize economic, social and ecological benefits (Rood et al. 2005; Konrad et al. 2012).

Integrated hydro-economic modelling tools have been developed to integrate economic efficiency and equity objectives in river basins (Ringler and Cai 2006; Ward et al. 2006; Pulido-

Velazquez et al. 2008). These studies have used a range of deterministic and stochastic - single to several objective problem formulations. In recent studies, advanced multi-objective optimization algorithms that rely on pareto-optimal curves or surfaces have been developed (Kasprzyk et al. 2009; Kollat et al. 2011; Fu et al. 2012; Reed et al. 2013; Marton and Kapelan 2014; Chu et al. 2015; Roach et al. 2016).

Most of the case studies that applied multi-objective optimizations focus solely on the blue water use in the basin, i.e. the water in rivers, aquifers, natural lakes and man-made reservoirs, ignoring green water use – landscape water uses that rely on rainfall. However, water management in a river basin should not be limited to the allocation of blue water only, but extend to include green water use as well, if we aim to manage water resources in a truly integrated manner. Although rainfed agriculture, which relies on green water, generates most of the food in Africa, its productivity per hectare remains low (Rockström 2003; Pingali 2012). A key strategy to upgrade rainfed agriculture is investing in supplementary irrigation to bridge dry spells (Barron et al. 2003; Falkenmark and Rockström 2006). Improved water productivity in rainfed systems can be significantly increased with relatively little additional water use (Molden et al. 2007). An enhanced green water use will, however, inevitably result in a change in blue water availability further downstream.

In this study, a multi-objective exploration of trade-offs in competing water uses is analysed for the Pangani River Basin in East Africa. The enhanced crop production resulting from supplementary irrigation and the reduced green water use due to soil and water conservation in rainfed systems were also integrated into the IHEM.

The following section outlines the Pangani river system. Section 3 describes the IHEM set-up for the lower Pangani hydro-system and the model scenarios. The results and discussion are presented in Section 4, and finally the conclusions are given in Section 5.

2. Pangani River system

The Pangani River system, located mainly in northern Tanzania with a small part in southern Kenya, starts at the mountains of Mt. Meru, Mt. Kilimanjaro, and the Pare and Usambara mountains and runs through the semi-arid middle course into the Pangani estuary in the Indian Ocean. The Upper Pangani River Basin, defined as the catchment area upstream of Nyumba ya Mungu (NyM) reservoir, is the main source of water (blue water) for the lower Pangani Basin (Kiptala et al. 2013a; 2013b). The Kikuletwa and Ruvu rivers provide water for hydropower and irrigation and provide essential environmental flows to maintain key ecosystem services such as the Kirua swamp and the Pangani estuary. The water resources are supplemented by the Mkomazi, Soni and Luengera rivers along the downstream river system that stretches for over 500 km (Fig. 1).

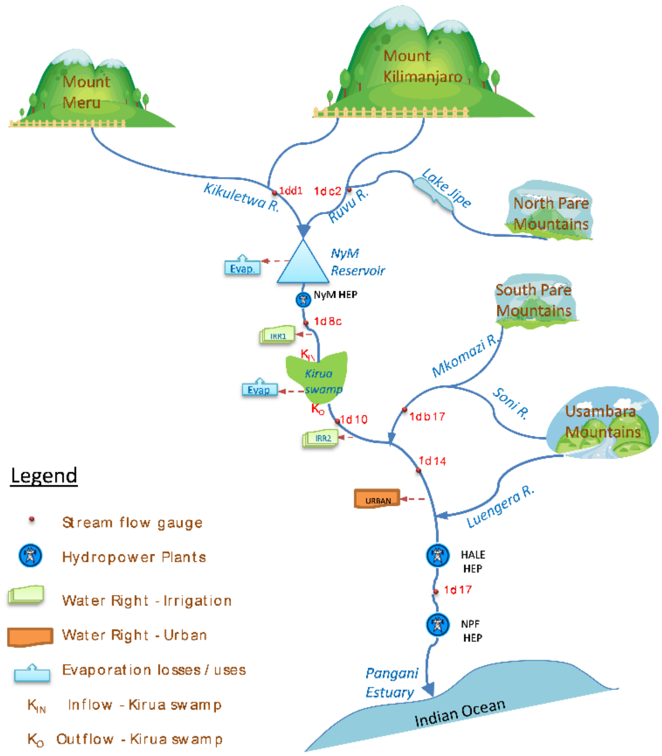

Fig. 1. Schematic layout of the Pangani River System

The three hydro-electric power stations (HEPs) in the lower Pangani, NyM (8 MW), Hale (21 MW) and New Pangani Falls (NPF) (68 MW), together contribute 17% of total installed hydropower to the Tanzania national grid. Table 1 presents the salient features of reservoirs and hydropower systems in Pangani river system.

Table 1. Salient features of reservoirs and hydropower systems in Pangani river system.

		NyM	Hale	NPF
<u>Reservoir</u>				
Commissioning	Year	1968	1965	1995
Catchment area	km^2	12,100	42,200	42,200
Max. supply level	masl	688.45	331.0	177.5
Min. supply level	masl	679.62	329.8	176.0

Total reservoir storage capacity	Mm^3	1,140	0.14	1.4
Active storage capacity	Mm^3	600	0.13	0.8
Long term average inflow	$Mm^3\ yr^{-1}$	1,100	730	730
Residence time	T	200 days	1.6 hrs	9.6 hrs
<u>Power plant</u>				
Installed capacity	MW	2×4	2×10.5	2×34
Max. design discharge	$m^3\ s^{-1}$	35	45	45
Min. design discharge	$m^3\ s^{-1}$	9.8	8.5	9
Max. operating head	m	27	63	170
Min. operating head	m	21	62	168
Machine efficiency	%	87	76	93
Average annual energy	$GWh\ yr^{-1}$	35	93	341
Firm Annual Energy	$GWh\ yr^{-1}$	20	55	201

"Source: Data from PBWO/IUCN (2009)."

NyM dam has dramatically changed the river regime in the lower Pangani hydro-system from bi-annual flooding of the Kirua swamp to a fully controlled flow in the river channels. This has led to the reduction of Kirua swamp from an average surface area of 852 km^2 to just 10 km^2 (PBWO/IUCN 2008). The lower Pangani River basin has high potential for irrigated agriculture. According to records at Pangani Basin office, by 2010, a total flow of 3.12 $m^3\ s^{-1}$ ($8\times10^6\ m^3$ $month^{-1}$) had been issued for water rights for smallholder irrigation systems here.

The operation policy for NyM reservoir is mainly aimed at regulating flows for the generation of firm energy at the three HEPs (Moges 2003). A discharge of 15 $m^3\ s^{-1}$ ($39\times10^6\ m^3\ month^{-1}$) is maintained as the minimum discharge to guarantee firm energy production at Hale and NPF power stations (Andersson et al. 2006). The firm energy production is the energy production with

90% reliability (TANESCO 2014). The energy production, transmission and distribution is managed by Tanzania Electric Supply Company Limited (TANESCO) - a state owned utility company.

The Energy and Water Utilities Regulatory Authority (EWURA) is an autonomous multi-sectoral regulatory authority which determines the electricity tariffs in Tanzania (EWURA 2012). The electricity tariff comprises of three segments namely generation, transmission, and distribution and supply. The price for the electricity generation segment corresponds with the tariff for bulk power supply to the island of Zanzibar which is US$ 80 MWh^{-1} (EWURA 2012). The price for alternative thermal sources is derived from the prices of bulk supplies by independent power producers (IPPs) to TANESCO which is approximately US$ 160 MWh^{-1} (MEM 2013). These values are used in this study to evaluate the hydropower generation benefits and their opportunity costs.

NyM power plant is a storage HEP while Hale and NPF operate as run-of-river systems. Through the construction of the NyM reservoir, the annually flooded area has reduced and vast areas have been extensively inhabited by local populations. The release from NyM reservoir is limited to 25 $m^3 s^{-1}$ for the river banks not to overflow to human settlements at Kirua swamp (PBWO/IUCN 2007). The low-lying Kirua swamp consumes water released from NyM reservoir through ground water recharge, transpiration and/or evaporation of up to 5 to 6 $m^3 s^{-1}$ (PBWO/IUCN 2007; Turpie et al. 2003; Andersson et al. 2006).

NyM reservoir is a shallow dam with high evaporation losses (PBWO/IUCN 2007). The minimum operating level for the reservoir corresponds to a minimum surface area of 40 km^2. The minimum surface area at NyM reservoir is considered sufficient to provide for environmental benefits to the local communities (Musharani 2012). The salt intrusion at the

Pangani estuary has been prevented by the minimum discharge of 15 m^3 s^{-1} released from the NPF HEP that is located 72 km upstream of the Indian Ocean. Sotthewes (2008) using a steady state salinity distribution model (Savenije 2005) showed that the salinity profile reaches up to 5.5 km with a minimum discharge of 10 m^3 s^{-1}. However, the salt intrusion would increase exponentially to 32 km upstream with a discharge of 5 m^3 s^{-1}.

Pangani estuary is rich in mangrove resources that offer ecosystem services to local populations. There are at least 8 species of mangroves that cover an area of 1,750 hectares (Turpie et al. 2003). The mangroves are mainly harvested for construction purposes and mostly exported to Zanzibar. The mangroves require both high and low flow conditions to sustain their growth (Alleman and Hester 2011).

The major users of the lower Pangani Basin therefore are HEPs, Kirua swamp, irrigation and urban water users, and the Pangani estuary. The competition between the demands of these water users and the upstream agriculture is analysed through an IHEM that is described in the following section.

3. Materials and Methods

IHEM is the central component of the multi-objective analysis (MOA). The IHEM for Pangani River Basin is coupled to the STREAM (Spatial Tools for River Basins and Environment and Analysis of Management Options) model, a fully distributed hydrological model (Aerts et al. 1999). The STREAM model accounts for green water use in the upper catchments and subsequent changes in blue water flows to NyM reservoir. NyM reservoir regulates the flow into the lower Pangani river system, with the predominantly blue water users – irrigators, hydropower and environment. The optimisation is done using the general algebraic modelling system (GAMS) programming language (GAMS 2015).

The objective functions for optimization were developed for key water users in the basin. To reduce the complexity of the MOA, the desirable level of some objectives, mainly non-monetary, were predetermined through field investigation, by stakeholders and/or by expert knowledge. These model constraints specify firm energy requirement, specific water supply for smallholder irrigation and urban water use, flood flow restrictions, and environmental flow requirements at both the Kirua swamp and the Pangani estuary. The objective functions and model constraints are described in the following sections.

The hydropower, supplementary and full irrigation benefit functions, which are valued in monetary terms, are considered as primary objectives subject to the predetermined constraints based on their desired levels. The trade-offs between the various objectives are then identified by removing or relaxing each constraint in the problem formulation. An overview of the methodological framework is presented in Fig. 2.

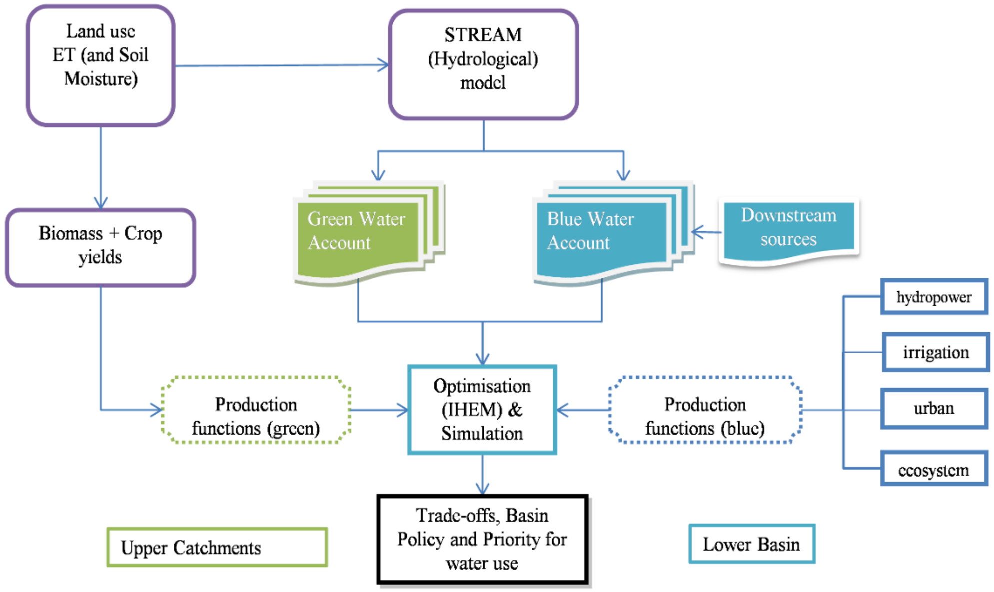

Fig. 2. Methodological framework for the multi-objective analysis

3.1 STREAM hydrological model

A fully distributed hydrological model (STREAM) developed by Kiptala et al. (2014) is used to simulate river discharge for the period 2008-2010 for the Upper Pangani River Basin. The STREAM model relies on remotely sensed data on actual total evaporation (Kiptala et al. 2013b) and land use and land cover (Kiptala et al. 2013a). The STREAM model is used to quantify green and blue water uses, including supplementary and fully irrigated agriculture in the Upper Pangani upstream of the NyM reservoir. The STREAM model simulates the blue water flows (river, groundwater) into the lower Pangani hydro-system at the NyM reservoir under various green water use scenarios at the upstream basin.

3.2 Biomass and crop yield

The analysis for biomass production relied on MODIS satellite data of 250-m and 8-day resolutions and SEBAL model utilizing Monteith's framework for ecological production (Kiptala et al. 2013b; Kiptala 2016). Grid biomass production (kg ha^{-1}) is converted into crop yield using relevant yield conversion factors.

3.3 The Integrated Hydro-Economic Modelling Approach

Whereas the formulation of an IHEM has no universal set-up, such a model adheres to the following essential requirements: a) consistent accounting of flows, water storages, and diversions, b) representation of demand for water and economic benefits for its use, c) network representation of a physical basin, and d) incorporation of institutional rules and policies (Cai et al. 2006).

Water availability is determined by the water balance in the river system, while water demand is determined exogenously based on calculations of water requirements for irrigated agriculture, hydropower, issued water rights and estimated environmental flow requirements. Our model is schematized as a node-link network representing the spatial relation between various off- and in-stream demands in the river basin (Fig. 3).

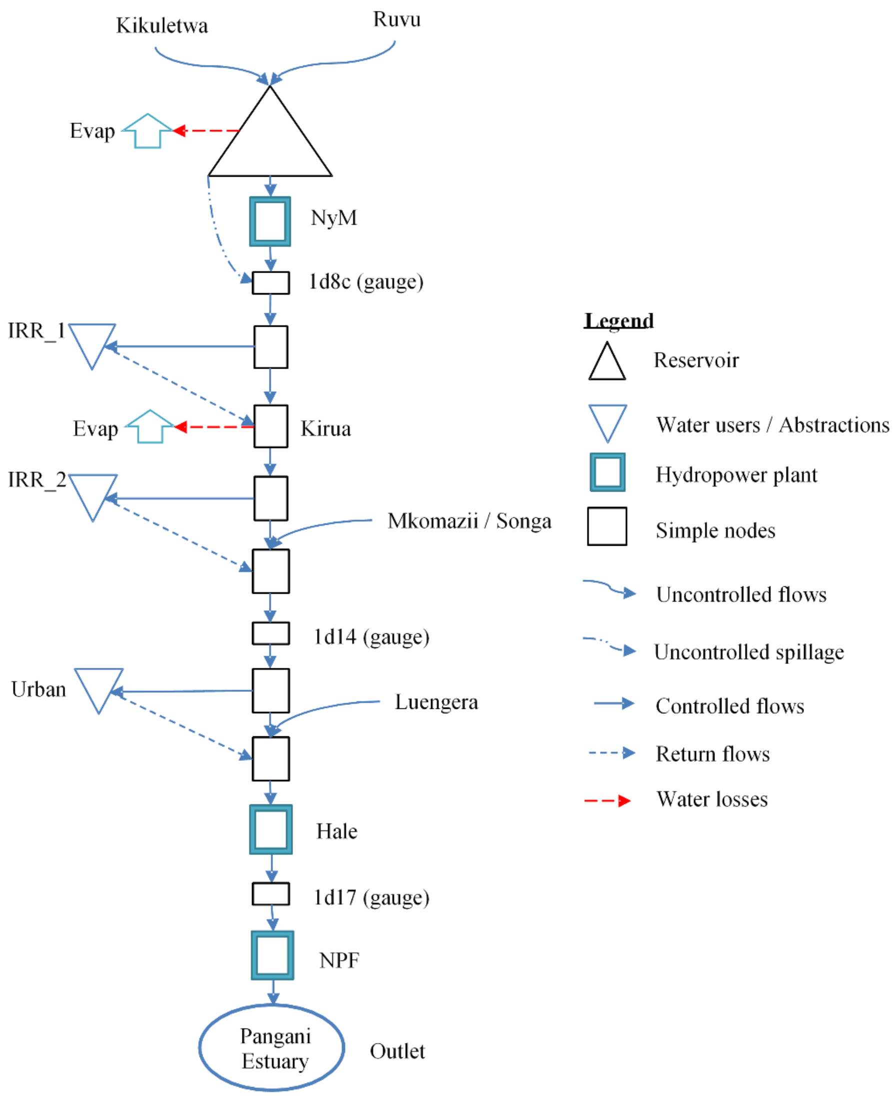

Fig. 2. Schematic structure of Lower Pangani hydro-system

The nodes represent the demand sites and links represent the river reaches. The nodes include simple nodes, source nodes at which inflows occur, reservoir nodes, and demand nodes. Each node should fulfil the water balance requirement. For the source and simple node, there is no storage considered. The releases from these nodes are equal to the total inflows. The equations that govern the mass balance for the source and simple nodes, Eq 1-3:

$$Q_{out}(n,t) = Q_{in}(n,t) \qquad (1)$$

where

$$Q_{out}(n,t) = \sum_{j \in D_n} q_{n,j}(t) \qquad (2)$$

$$Q_{in}(n,t) = \sum_{j \in U_n} q_{i,n}(t) \qquad (3)$$

$q_{n,j}(t)$ represents flow (Mm^3/month) from node n to node j, D_n is the set of all the nodes that are immediately downstream of node *n* and U_n is the set of all the nodes that are immediately upstream of node *n*.

$Q_{out}(n,t)$ is the release from the node *n* in period *t*, that is distributed over the downstream nodes. $Q_{in}(n,t)$ is the source of water or for the simple nodes the inflows at the time period *t*. Depending on the requirements at each node, water is either diverted to users or remains in the river.

In the Kirua swamp (*KS*), the simple node that represents the release of flow to the area between the upstream node and downstream node is given by an empirical equation developed by IVO-NORPLAN (1997) (Eq. 4, all units in $m^3\ s^{-1}$):

$$Q_{out}(KS,t) = -0.005 Q_{in}(KS,t)^2 + 0.9193 Q_{in}(KS,t) - 1.0308 \qquad (4)$$

Eq. 4 holds for $Q_{in}(KS,t) < 25\ m^3\ s^{-1}$ and any excess inflows (> 25 $m^3\ s^{-1}$) would drain out of the river system and is consumed by the wetland.

Reservoir nodes are different as they consider storage. Here, we only consider the NyM storage reservoir and the Eq. 5-7 applies for period t (Loucks et al. 1981):

$$(1+\alpha_t)S(n,t)=(1+\alpha_t)S(n,t-1)+Q_{in}(n,t)-Q_{out}(n,t)-\beta_t \qquad (5)$$

where

$$\alpha_t=\frac{A_a E_o(n,t)}{2} \qquad (6)$$

$$\beta_t=A_o E_o(n,t) \qquad (7)$$

$Q_{in}(n,t)$ and $Q_{out}(n,t)$ are defined in Eq. 2 & 3 and S is the storage (Mm^3), A_o is the water surface area corresponding to the dead storage (km^2), A_a is the water surface area per active storage volume above the dead storage level (km^2), and $E_o(n,t)$ is the evaporation rate in node n in period t (Loucks et al., 1981). The monthly evaporation rate is derived from pan evaporation measurements at NyM reservoir. The open water evaporation is computed using a pan coefficient factor of 0.81 (Kiptala et al. 2013b).

The water surface areas are computed from the reservoir area - volume equations derived from the original design report of NyM dam by Sir William Halcrow & Partners (1970):

$$V=(H/649.59)^{11227} \qquad (8)$$

$$A=(H/651.59)^{88.15} \qquad (9)$$

where V is the reservoir volume (Mm^3), A is the surface area of reservoir (km^2) and H is the water level in metres above sea level (m.a.s.l).

3.4 Multi-objective problem formulation for the Pangani hydro-system

Dynamic programming is a widely used optimization technique to determine optimal operating policies (Loucks et al. 1981). The objective of the reservoir operation problem optimization is to derive optimal release decisions as a function of variables describing the state of the system. The objective function therefore seeks to maximize benefits for each water sector subject to hydrological constraints (Eq. 1–7). For water use that comprise in-stream use such as hydropower, and off-stream functions such as irrigation, the water value is derived from the accumulated benefit functions to account for the cyclic nature of water use (Pande et al. 2011).

Two objective functions were considered that seek to maximize irrigated agriculture (f_{ag_I}) and rainfed agriculture (f_{ag_R}) in the upper catchment while one objective function to maximize hydropower (f_{hydro}) was considered in the lower Pangani hydro-system. The optimisation problem formulation (Eq. 10) is consistent with Tilmant et al. (2007), Kasprzyk et al. (2009) and Hurford and Harou (2014):

$$F(x) = \left(f_{ag\_I},\, f_{ag\_R},\, f_{hydro}\right) \qquad (10)$$

$$\forall\ x \in \mathbf{\Omega}$$

where x is the optimized water diversions and reservoir release for the set of water dependent sectors ($\mathbf{\Omega}$).

The objective functions are subject to four constraints that include firm energy (f_{firm}), fulfilling water rights for smallholder farmers and urban water use in the mid-stream (f_{WR}), and environmental requirements for the Kirua swamp (f_{kirua}) and Pangani estuary ($f_{estuary}$). The model runs on a monthly time step with an optimisation period of 3 years (36 time steps). The problem formulation is solved using the GAMS MINOS solver (McKinney and Savitsky 2003).

The following sections details the various water uses.

3.4.1 Fully irrigated agriculture

The objective function for the fully irrigated agriculture is to maximize the proceeds from the expansion of the sugarcane irrigation project to its potential.

$$f_{ag\_I} = \max\left(P_{n(s)} \times S_s \times Y_s \times \prod_t \left[\frac{W_r\ (t)}{W_d\,(t)} \right]^{l(t)} \right) \tag{11}$$

$$S_s < S_{p(s)} \tag{12}$$

where $P_{n(s)}$ is the net farm gate price of sugar (US\$ kg^{-1}), S_s is the irrigation area (ha), $S_{p(s)}$ is the potential (sugarcane) irrigation area (ha), Y_s is the yield (kg ha^{-1}), t is the time index (month), $W_r(t)$ is the water diverted in each time period (Mm^3 month^{-1}), $W_d(t)$ water demand in each time period (Mm^3 month^{-1}) and $l(t)$ is the stress coefficient for sugarcane for each time step (equivalent to 1.2).

The potential irrigation area for irrigated sugarcane is 7,400 ha.

3.4.2 Supplementary irrigated agriculture

The objective function for supplementary irrigated agriculture (in the upper catchment) is to enhance yields in rainfed systems by increasing productive transpiration (*T*) through supplementary irrigation. The impact of enhancing green water use would result in reduced blue water flows downstream (Kiptala et al. 2014). It was shown by Makurira et al. (2012) that an increase of productive T of up to 47% can be achieved in rainfed systems in the Pangani Basin. An increase in total ET (includes soil evaporation) of 30% can achieve relatively high T since part of soil evaporation would be shifted in favour of T (Makurira et al. 2012). The concept of vapour shift in green water use has been described in more details by Rockström (2003).

Kiptala (2016) developed an analytical relationship between biomass production (B_{acc}) and ET for rainfed and supplementary irrigated agriculture (sup.irr):

$$B_{acc\_\text{rainfed}} = 3.9ET - 2.1 \tag{13}$$

$$B_{acc\_\text{sup.irr}} = 5.3ET - 2.6 \tag{14}$$

where B_{acc} is the accumulated biomass production in kg ha^{-1} yr^{-1} and ET is the total evapotranspiration in m^{3} ha^{-1} yr^{-1}. The management scenarios for enhanced green water use provided in Kiptala et al. (2014) results in increased biomass production. An average rate of change in biomass production from Eq. 13 and Eq. 14 is adopted since the interventions would yield a hybrid agricultural system. Rainfed maize crop is considered with a potential area for improvement of 36,000 ha. The change in biomass production, B_{acc} (kg ha^{-1} yr^{-1}) due to an increase in green water use (Q_{g_b}) is converted into yield (Y_{mz}) using an effective harvest index of 0.35 for maize (i.e. $Y_{mz} = 0.35 \times B_{acc}$) (Wiegand et al. 1991; Kiptala 2016).

The objective function to be maximized for supplementary irrigated agriculture therefore becomes:

Maximize $$f_{ag\_R} = P_{n(mz)} \times Y_{mz} \times \sum_{t}^{T} \left(\frac{Q_{g\_b}}{Q_{g\_d}} \right) \quad (15)$$

$$Q_{g\_b} < \left(Q_{g\_d} \times S_{p(r)} \right) \quad (16)$$

where $P_{n(mz)}$ is the (net) farm gate price of maize (US\$ kg^{-1}), Y_{mz} is the additional yield per hectare for maize (kg ha^{-1}), Q_{g_b} is the additional green water use in rainfed area per month (Mm^3 $month^{-1}$), Q_{g_d} is the additional green water demand per hectare (Mm^3 ha^{-1} $month^1$) and $S_{p(r)}$ is the potential rainfed area (ha).

An addition to the above intervention, another intervention aiming to reduce soil evaporation (E_s) in supplementary irrigated crops (maize) in the Upper Pangani River Basin by 15% was considered. The reduction in E_s by 15% resulted in a water saving (Q_{ws}) that was quantified using the STREAM model (Kiptala et al. 2014).

3.4.3 Hydropower production

The production function of hydropower is used to derive its benefit function. The production function is a nonlinear function of the head (storage) and release variables. Power output P_y (Nm s^{-1} or W) and energy output E_y (Nm or Ws) is a function of discharge Q_p and head H_e derived using Eq. 17 (Revelle 1999).

$$P_y = e_t e_g \, \rho \, g \, Q_p \, H_e \quad (17)$$

where Q_p is the plant discharge (m^3 s^{-1}), ρ is the density of water (kg m^{-3}), g is the acceleration due to gravity (~9.81 m s^{-2}), H_e is the effective water head (m) (static water head – head loss) and

$e_t e_g$ is the turbine and generator efficiency. The hydropower energy produced is therefore computed using Eq. 18.

$$E_y = P_y \times T_g \qquad (18)$$

where, E_y is the Energy output (W s) and T_g is the generating time (s).

The optimization problem can be made linear by assuming that the production of hydroelectricity is dominated by the release term and not by the head (or storage) term. This assumption is valid as long as the difference between the maximum and minimum heads is small compared to the maximum head (Wallace and Fleten 2003). This assumption was used for main HEPs; Hale and NPF run-of-river systems where the difference between maximum and minimum operating head is small (Table 1).

The objective function for hydropower is to maximize the hydropower benefits from the water release at NyM reservoir. The bulk hydropower energy price is US$ 80 MWh^{-1}. The opportunity cost for hydropower is estimated from the cost of despatching alternative thermal sources or cost of bulk electricity purchases from IPPs which is equivalent to US$ 160 MWh^{-1}. A similar approach was adopted by Kiptala (2008) and Hurford and Harou (2014) for the Tana River Basin in Kenya. The objective function is to maximize returns from the hydropower production in all the HEPs, Eq. 19.

$$f_{hydro} = \max\left(\sum_{1}^{36} \sum_{i} \left(Hydro_{revenue} \right) \quad i \in \{Nym, Hale, NPF\} \right) \qquad (19)$$

Eq. 19 is subject to the minimum monthly firm energy requirement at the NyM, Hale and NPF hydropower stations. The firm energy is formulated as a model constraint to minimize the deficits from the minimum monthly requirements, Eq. 20.

$$f_{firm} = \min\left(\sum_{1}^{36}\sum_{i}\left(Deficit \rightarrow Firm_{energy}\right) \quad i \in \{Nym, Hale, NPF\}\right) \qquad (20)$$

3.4.4 Full irrigation and municipal water rights in the lower Pangani basin

According to the Pangani Basin office, there are 29 water abstraction canals for smallholder agriculture in the lower Pangani Basin with aggregated water rights of 3.12 $m^3 s^{-1}$. The irrigation canals supply water to community development projects for food production, domestic use as well as for livestock. Lemkuna, Naururu, Ngage are the main irrigation canals with water rights of 0.5 $m^3 s^{-1}$ each. An assessment of water flows between gauge station 1d8c at NyM and 1d14 at Korogwe (Fig. 1), minus water uses in the lower basin including the water losses at Kirua Swamp (using Eq. 4), showed a consistent irrigation water use of 3.14 $m^3 s^{-1}$. Korogwe town has a water right of 0.83 $m^3 s^{-1}$ for domestic water supply and used to a smaller extent by a sisal factory.

Since the objective of water allocation to these users is social rather than economic, the optimization problem is formulated to minimize deficits to their water rights provisions for irrigation (*I*) and urban (*U*), Eq. 21. A similar approach was adopted in a case study in Turkey by Gurluk and Ward (2009).

$$f_{WR} = \min\left(\sum_{1}^{36}\sum_{i}\left(Deficit \rightarrow WR\right) \quad i \in \{I, U\}\right) \qquad (21)$$

3.4.5 Environmental requirements

Demand curves for environmental benefits can be derived from the environmental goods and services that are provided to sustain ecosystems and to the environment by the water use. This however requires detailed environmental valuations that are linked to the hydrologic (supply) conditions and environmental benefits. This information is difficult to derive or estimate though there is a general understanding that valuing water should account for environmental and social values (Hermans et al. 2006). An alternative approach is to remove the environmental flows from the objective function and treat them as additional constraints, thereby giving them priority (George et al., 2011). The flow regime representing the lower bounds, i.e. the minimum flow requirements in space and time or flow constraints, could then be changed in order to establish the trade-off relationship. This approach requires an accurate hydrological assessment of the environmental flow requirement for the river basin.

Water use at the Kirua swamp is conditioned in the model using Eq. 4 for flows less than 25 m^3 s^{-1} to account for water use in the wetland. The maximum flow of 25 m^3 s^{-1} is imposed (on inflow) to prevent overtopping of river banks and flooding of areas currently occupied by local populations. These flow constraints will be removed in the model to assess the trade-off with the other water users.

Presently, there is no study on the environmental flow requirements for mangroves growth in the Pangani estuary before or even after the construction of the dams. The model requirement for a maximum low flow during the dry period and a minimum high flow during wet seasons is therefore unknown and is not considered in this study. The study, however uses maximum flow targets to assess implicitly the environmental flows. Since there no evidence of any damage on the mangroves since the construction of the dams, conclusions will be drawn on the sustainability of the flow targets.

For the minimum environmental flow (low flow, dry season) for the estuary, the study adopts the discharge of 10 $m^3\ s^{-1}$ to minimize the impact on salt intrusion in the Pangani estuary (Sotthewes, 2008).

The peak flows during the wet season are considered to be largely provided by the unregulated Mkomazi and Luengera rivers.

The resulting objective function for environmental flows then becomes:

$$f_i = \min\left(\sum_{1}^{36}\sum_{i}\left(Deficit\right) \quad i \in \{Kirua, Estuary\}\right) \tag{22}$$

All the model constraints are summarized in Table 2.

Table 2. Secondary objectives considered in the Pangani hydro-system optimization model

	Model constraints
f_{firm}	Minimum discharge of 39 Mm^3 $month^{-1}$ (15 $m^3\ s^{-1}$) at Hale and NPF HEPs to guarantee firm energy.
f_{WR}	2.3 Mm^3 $month^{-1}$ (0.83 $m^3\ s^{-1}$) urban & 8.1 Mm^3 $month^{-1}$ (3.12 $m^3\ s^{-1}$) small-scale irrigation water rights
$f_{estuary}$	26.4 Mm^3 $month^{-1}$ (10 $m^3\ s^{-1}$) at the outlet
f_{kirua}	Release, $Q_{out}(KS,t)$ at Kirua conditioned by Eq. 4 for $Q_{in}(KS,t) \leq$ 65.0 Mm^3 $month^{-1}$ (25 $m^3\ s^{-1}$)

3.4.6 Problem formulation

The problem formulation is carried out in two phases. The first phase involves the blue water use in the lower Pangani hydro-system. In this phase, the current demand case (base scenario) is used to validate the IHEM and includes all the model constraints. The constraints are then removed or relaxed one by one in subsequent scenarios (Table 3).

Table 3. Problem formulations for blue water use in the Lower Pangani hydro-system

Scenario	Primary objective	Model constraints	Remarks
1 (Base)	f_{hydro}	f_{firm}, $f_{WR,}$ $f_{Kirua,}$ $f_{estuary}$	*ALL*
2	f_{hydro}	$f_{WR,}$ $f_{Kirua,}$ $f_{estuary}$	*No firm energy*
3	f_{hydro}	f_{firm}, $f_{Kirua,}$ $f_{estuary}$	*No Water rights*
4	f_{hydro}	f_{firm}, $f_{WR,}$ $f_{estuary}$	*No Kirua*
5	f_{hydro}	f_{firm}, $f_{WR,}$ f_{Kirua}	*No Estuary*

The base scenario provide the baseline water balance of the lower Pangani hydro-system. Subsequently, the IHEM is integrated with the green water use options in the upper catchments (Table 4).

Table 4. Problem formulations for green and blue water use in Pangani Basin

Scenario	Primary objectives	Constraints	Remarks
A	f_{hydro}, f_{ag_I} , f_{ag_R}	*ALL*	*All objective functions*
B	f_{hydro}, f_{ag_I} , f_{ag_R}, Q_{ws}	*ALL*	*All objective functions plus water savings in agric.*
C	f_{hydro}, Q_{ws}	*ALL*	*Base scenario plus water saving in agric.*

The intervention for the reduction in soil evaporation (E_s) by 15% in supplementary irrigation (mixed crops) through water conservation (Q_{ws}) is evaluated with all the objective functions (scenario B) and base demand case (scenario C).

4. Results and Discussion

This section provides the results of the optimized scenarios. The present demand case (scenario 1) has been used to validate the simulated results and generate the baseline water balance for the lower Pangani hydro-system. The model validations are presented as Supplementary Data. Figures S1 – S3 in the supplementary information shows that good correlations were achieved between observed and simulated discharges and hydropower production in the lower Pangani Hydro-system.

4.1 Water balance for the lower Pangani hydro-system

The simulated evaporation losses at NyM reservoir were estimated at 7.9 $m^3 s^{-1}$, about 28% of the total inflow (27.8 $m^3 s^{-1}$) into NyM reservoir for the period 2008 - 2010. The simulated evaporation is within the upper limit of the range of 4 - 8 $m^3 s^{-1}$ reported in the literature (Turpie et al. 2003; Andersson et al. 2006). The NyM reservoir releases an average of 20 $m^3 s^{-1}$ of which an average of 4 $m^3 s^{-1}$ is utilized for environmental functions in Kirua swamp, and another 4 $m^3 s^{-1}$ for irrigation and urban water use. Mkomazi and Luengera rivers injects an additional 6 $m^3 s^{-1}$ into the lower Pangani hydro-system, yielding an average total outflow of 18 $m^3 s^{-1}$ to the Pangani estuary (Fig. 4).

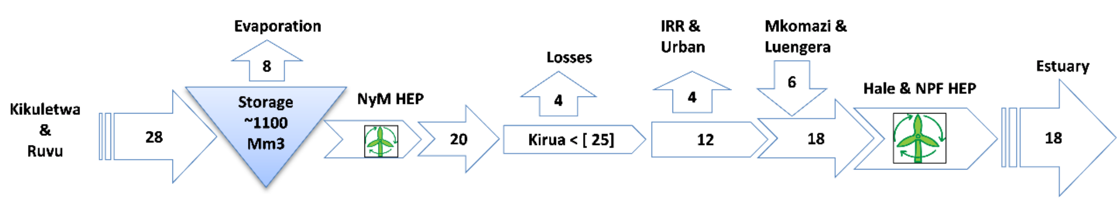

Fig. 4. The water balance (in $m^3 s^{-1}$) for Lower Pangani hydro-system for the period 2008 – 2010

Overall this shows that the model is able to simulate the system credibly and was therefore used for the optimisation scenarios.

4.2 Optimisation scenarios for the lower Pangani hydro-system

Table 5 presents the results of the five optimisation scenarios (Table 3). In scenario 1 (base scenario), the benefit functions of all water users (including the constraints) are incorporated in the problem formulation. It resulted in total hydropower production of 355 GWh yr^{-1}, equivalent to US$ 28 million yr^{-1} in energy revenue. For the other scenarios where certain constraints were removed, hydropower increases, this implies that maximising hydropower production affects other water users in the basin.

Table 5. Trade-off in hydropower between water users in Lower Pangani hydro-system.

HEP	NyM			Hale			NPF			Total	
	GWh yr^{-1}			GWh yr^{-1}			GWh yr^{-1}			Energy	Revenue
Scenarios	2008	2009	2010	2008	2009	2010	2008	2009	2010	GWh yr^{-1}	US$ Million yr^{-1}
1 (Base)	36	41	33	90	61	71	297	201	233	355	28
2	54	30	23	124	*47*	57	410	*156*	*188*	364	29
3	50	33	27	128	63	74	420	204	244	416	33
4	54	31	26	152	61	73	500	201	241	447	36
5	36	41	33	90	61	71	297	201	233	355	28
Firm		20			55			201		276	22

“Note: values in italics indicate the years when the firm energy requirement has not been met

Scenario 2 shows that removing the firm energy benefit function, changes the operations of NyM reservoir. In the optimisation, the water levels were maintained at a lower head to reduce evaporation losses. The release policy provides more naturalized flow conditions where high flows were released during the wet year and low flows during dry years. The simulated evaporation loss at NyM reservoir was reduced from 7.9 to 6.7 $m^3 s^{-1}$. However, the water use (losses) of Kirua swamp increased from 4.4 to 4.9 $m^3 s^{-1}$. Total hydropower production in this scenario increased, however firm energy requirements were not met in two of the three HEPs.

It is noteworthy that the cost for failing to meet the guaranteed firm energy production may be higher than the savings realized if emergency thermal systems that have high short run marginal costs were dispatched. However, if high capacity alternative energy sources like geothermal were available, then the hydropower production can be optimized within the naturalized flow regime. Examples of re-optimization techniques on reservoir operation and river restorations have been presented by Jacobson and Galat (2008). The re-designed reservoir policy would result in high energy production during wet seasons and low energy production during dry seasons. Alternatively, the bulk energy prices could be varied seasonally, as for the case in Kenya (Kiptala 2008; Hurford and Harou 2014) and the independent providers invited to supply firm energy from thermal systems on long-term contracts. In such a case, the long term marginal cost of energy generation will be much lower.

Scenario 3 shows that removing the water rights requirements for smallholder irrigation and urban areas would increase the water allocation to the downstream HEPs. NyM reservoir similarly maintains a lower water level to minimize on evaporation losses. The evaporation at NyM reservoir is therefore reduced by 0.8 $m^3 s^{-1}$ which is nearly balanced out by increased water use of 0.7 $m^3 s^{-1}$ of Kirua swamp. The hydropower production increased especially in Hale and NPF HEPs resulting in additional revenue of US$ 5 million yr^{-1}. The existing water rights are therefore equivalent to an average of US$ 5 million yr^{-1} in foregone hydropower benefits (smallholder agriculture (US$ 4 million yr^{-1}) and urban water use (US$ 1 million yr^{-1})). The water rights for smallholder agriculture and urban supply compete with hydropower and also with environmental water uses.

In scenario 4, the flow restriction at, and water use of, Kirua swamp of 4 $m^3 s^{-1}$ was removed from the multi-objective function of the Pangani hydro-system. The optimal release policy at

NyM reservoir maintains a lower reservoir level to minimize evaporation losses due to reduced water requirements from Kirua swamp. The simulated evaporation losses reduced by 1 $m^3 s^{-1}$ at NyM reservoir to yield a total increased average outflow downstream of 5 $m^3 s^{-1}$. The annual energy production increased by 92 GWh yr^{-1} on average over the period. The Kirua swamp therefore has an economic value of US$ 8 million yr^{-1} in foregone revenue to hydropower using the bulk hydropower tariff of US$ 80 per MWh^{-1}.

The objective function on the minimum environmental requirement of 10 $m^3 s^{-1}$ at the Pangani estuary has no effect on the energy production (scenario 5). The high discharge requirement (15 $m^3 s^{-1}$) for firm energy at Hale and NPF HEP ensures that the minimum flow requirement for the estuary (downstream) was always met.

4.3 Problem formulation for green and blue water use

In this section, the three water management scenarios on increasing irrigated area, enhancing rainfed agriculture and reducing soil evaporation in the upper catchment were evaluated with the blue water uses in the lower Pangani hydro-system (see Table 4). Table 6 presents the optimization results.

Table 6. Green and blue water optimization scenarios in Pangani Basin. Values in italics indicate years when the firm energy requirement is not met.

HEP	NyM			Hale			NPF			Annual Totals		
										Energy	Revenue	Agric.
	2008	2009	2010	2008	2009	2010	2008	2009	2010	GWh	US$ Million	US$ Million
Base	36	41	33	90	61	71	297	201	233	355	28	-
A	27	31	25	76	*44*	59	249	*144*	*194*	283	23	55
B	28	32	26	79	*49*	62	261	*160*	205	301	24	55

C	44	41	33	104	61	71	342	201	233	376	30	-

In scenario A, the optimization model diverts river flow to the total potential irrigation area (7,400 ha) for sugarcane and for 36,000 ha of supplementary irrigated rainfed maize (highland crop). The resulting minimum flow is 11 $m^3 s^{-1}$, below 15 $m^3 s^{-1}$ that is required for firm energy. The water use (losses) at Kirua swamp reduces from 4.4 $m^3 s^{-1}$ to 3.2 $m^3 s^{-1}$. The reduction (1.2 $m^3 s^{-1}$) represents about 27% of the additional requirements for both sugarcane irrigation and the rainfed system (4.5 $m^3 s^{-1}$). The average energy production reduces by 72 GWh yr^{-1}. The firm energy requirement for Hale and NPF was also not met in dry (2009) and average years (2010). The total energy revenue reduces by US$ 5 million yr^{-1} or an increase in energy cost of US$ 10 million yr^{-1} if alternative power is sourced from thermal sources. The revenue loss is much lower than the additional income to agriculture for sugarcane (US$ 19 million yr^{-1}) and rainfed maize (US$ 36 million yr^{-1}). The revenue for increased sugarcane production is calculated for a sucrose yield of 10 tons ha^{-1} (sucrose), farm gate price of 0.6 US$ kg^{-1} and a relative cost of production of 58% (Kiptala, 2016). The area to be expanded for sugarcane irrigation is currently under grassland/woodlands which has a marginally low productivity, which is here neglected. The increase in transpiration in rainfed systems results in an increased biomass production of 15×10^3 kg ha^{-1} yr^{-1} in both *Masika* and *Vuli* seasons. The total revenue was derived from an effective harvest index of 0.35 and (net) farm gate price of US$ 0.19 kg^{-1}. It is noted that an additional 9,000 ha of rainfed agriculture can still be irrigated before the IHEM is fully constrained by the minimum flow requirements of 10 $m^3 s^{-1}$ at the estuary. It should be noted that the optimization results in a 27% reduction of water use by Kirua swamp, with an unquantified loss of benefits. Similarly, the minimum flow into the estuary reduces from 15 $m^3 s^{-1}$ to 11 $m^3 s^{-1}$ which is still above the minimum threshold of 10 $m^3 s^{-1}$ (also see Fig. S2 in supplementary data).

In scenario B, the inflow into the river system was increased by the reduction of soil evaporation in the supplementary irrigated agriculture. The additional inflow represents 27% of the additional water requirements for agriculture under scenario A. The water saving increased the energy production from scenario A by 18 GWh yr^{-1}. The water use by Kirua swamp slightly increased (from scenario A) with a reduction of 23% compared to the base scenario. The minimum flow to the estuary increased from 11 m^3 s^{-1} to 12 m^3 s^{-1}.

In scenario C, water saving without expansion in agriculture, the optimal policy maximizes hydropower production by maintaining a low operating reservoir level. The low reservoir operating level reduced the evaporation losses by 0.4 m^3 s^{-1} which is balanced by similar increased in water uses (losses) of Kirua swamp. In total, the energy production increases on average by 21 GWh yr^{-1} (all during the wet year 2008) resulting in additional revenues of US$ 2 million yr^{-1} or total energy revenue savings of up to US$ 4 million yr^{-1} from thermal sources.

The increased agricultural water use in the upper catchments reduces benefits from hydropower, firm energy and the environment. The analysis shows that agricultural water use upstream of NyM reservoir has a higher marginal water value compared to hydropower. The marginal water value for agriculture water use (blue water) is US$ 0.35 m^{-3} for irrigated sugarcane and US$ 0.37 m^{-3} for supplementary irrigated maize (Fig. 5). This is much higher compared with the accumulated marginal water value of US$ 0.05 m^{-3} for hydropower production (US$ 0.005 m^3 (NyM) + US$ 0.010 m^3 (Hale) + US$ 0.034 m^3 (NPF), equivalent to an energy water productivity of 0.05, 0.13 and 0.42 KWh m^{-3} for NyM, Hale and NPF respectively). This result is consistent with findings of multi objective optimization of water use between hydropower and irrigation in the Tana River Basin, Kenya (Kiptala, 2008; Hurford and Harou, 2014).

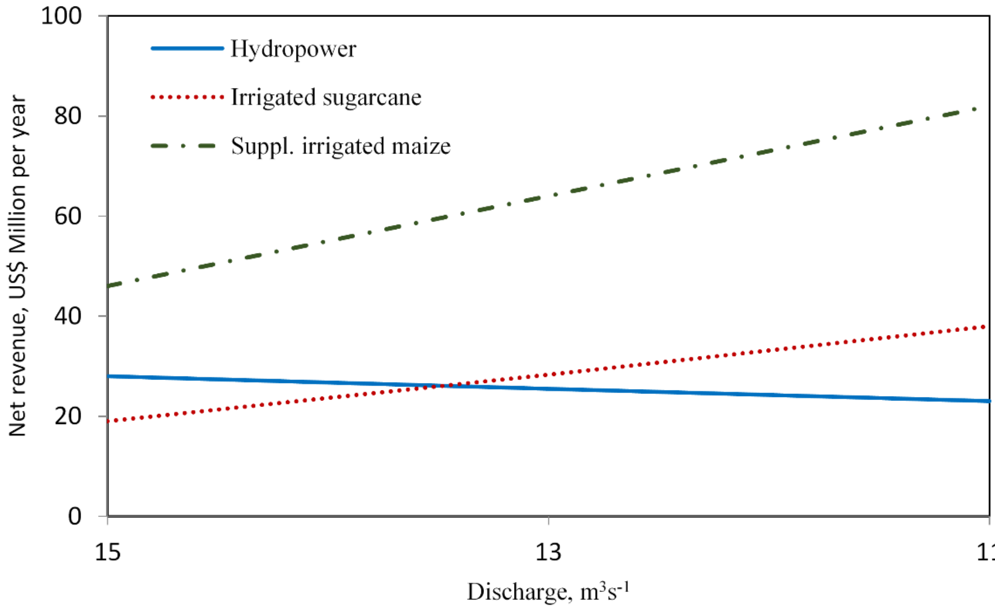

Fig. 5. Trade-offs between hydropower (downstream), agricultural water use (upstream) and discharge to Pangani estuary

5. Conclusion

This paper presents a novel way to increase the understanding of trade-offs between all water uses, including green water use, in a river basin. This is an innovative concept as previous studies to optimise water use predominantly focussed on blue water. The trade-off analyses show that hydropower, environment, urban and agriculture all have competing objectives. Firm energy that is guaranteed at 90% reliability maintains moderate flow conditions at all times, but competes with the environmental flow requirements which requires high and low flows.

Neglecting the flow requirements for Kirua swamp resulted in an increase in hydropower production by 24%, equivalent to US$ 8 million yr^{-1} in hydropower revenues. At the Pangani estuary, the minimum environmental flow requirement was met for all scenarios as this was lower than the water demand for firm energy. The high flow conditions at the estuary were provided and sustained by the uncontrolled inflows from Mkomazi and Luengera rivers. Future plans to control the river inflows from Mkomazi and Luengera tributaries should consider the environmental high flow requirement of the Pangani estuary.

NyM reservoir consumes a significant amount of water through evaporation (28% of its total inflows). The optimization results showed any intervention to increase water inflows into the lower Pangani hydro-system above the present state will result in a reservoir operating policy that reduces water levels and thus the evaporation losses at NyM reservoir. A reservoir operating policy that reduces water levels at NyM reservoir also benefits the environment. Water saving by reducing soil evaporation losses in irrigated agriculture in the Upper Pangani resulted in increased hydropower revenue of US$ 2 million yr^{-1}. This is equivalent to US$ 33 ha^{-1} yr^{-1} of investment in soil and water conservation in irrigated agriculture - a potential opportunity for payment for environmental services (PES). The value for soil and water conservation could double if the saving from expensive thermal energy sources were considered in the analysis. The increased water flow enhanced environmental services in the lower catchment as observed with the increased water use by Kirua swamp.

As expected, increased water use for agriculture (rainfed maize and irrigated sugarcane) resulted in decreasing benefits for hydropower production. The estimated additional benefits for increased agricultural water use (US$ 55 million yr^{-1}) were much higher than the benefits foregone from hydropower of between US$ 5 - 10 million yr^{-1}. However, the reduced flows affect the downstream ecosystems, whose benefits were not quantified in this study. Furthermore, the study showed that improving rainfed maize through supplementary irrigation during rainy seasons has a slightly higher marginal water value than full scale sugarcane irrigation.

With these analyses, the decision makers in the Pangani River basin have the knowledge to decide whether to allocate additional water for upstream agricultural development or to trade-off with hydropower subject to the water requirements for ecosystem services. Since hydropower is a non-consumptive water user, the operating policy of the NyM reservoir would be further optimized for the conjunctive use with the environment. This may involve interventions such as to lower the firm energy requirements which can be achieved by reducing dependency on hydropower in the river systems during dry periods. Alternative power sources, such as geothermal, and alternative institutional arrangements, e.g. through power purchase agreements, should be explored. However, this may result in higher energy prices during the dry seasons.

This novel methodological framework can be used by policy makers and stakeholders to identify holistically the impacts and opportunities of various water management decisions in the river basin. The developed methodology may be useful for highly utilised river basins with largely green water uses in the upper catchment and blue water uses in the lower basin.

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The data and the multi-optimization model used in this study can be obtained by request to the corresponding author.

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Supplementary Data to

Multi-objective analysis of the green-blue water uses in a highly utilized basin. Case study of Pangani Basin, Africa.

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Model validation

For scenario 1 (base), the goodness of fit between the observed and simulated water levels at NyM reservoir and the discharge at Korogwe (1d14) and the NPF (1d17) gauge stations were estimated using the coefficient of determination (R^2). The actual discharges at the outlet of NyM reservoir (1d8c) were not available for the period of analysis. The energy production was compared to firm energy production and the average historical energy production.

Fig. S1 shows observed and simulated water levels computed by base scenario (1) at NyM reservoir. The convergence of observed and simulated reservoir water level occurred after 8 time steps. The simulated and observed water levels after convergence showed a good correlation (R^2=0.99).

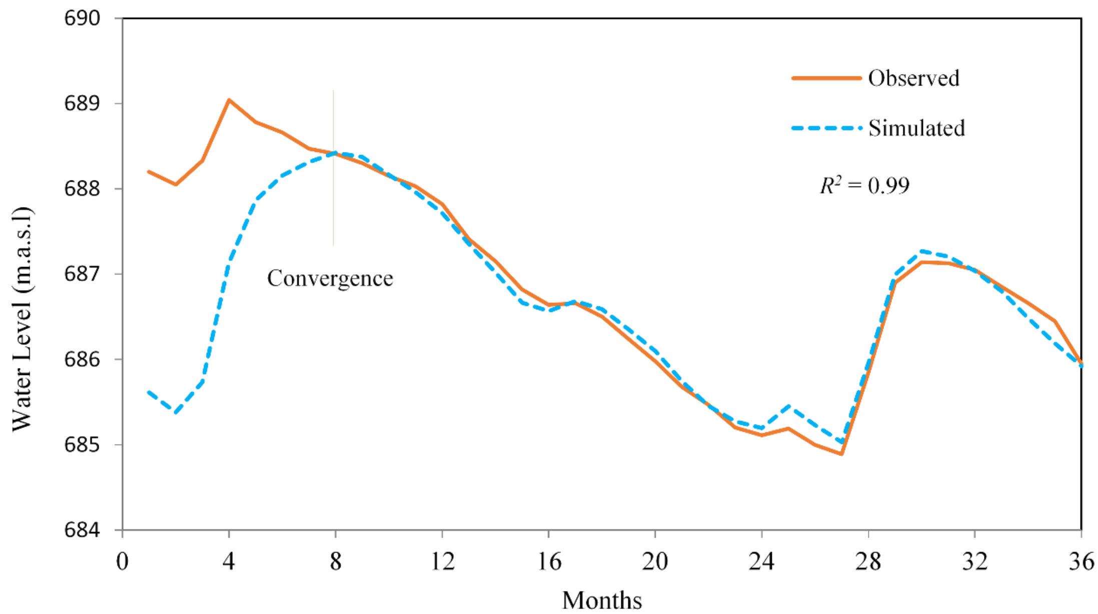
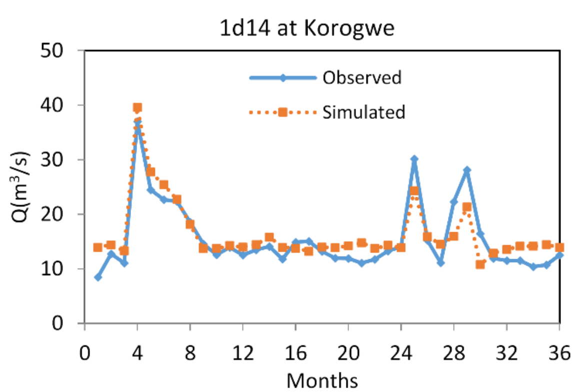


Fig. S1. Observed and simulated water levels in NyM reservoir for the period 2008 – 2010.

The simulated discharge and observed discharge at the downstream gauge stations 1d14 at Korogwe and 1d17 at Mnyuzi showed reasonably good correlations with R^2 of 0.7 and 0.8 respectively (Fig. S2). Station 1d17 is just downstream of Hale HEP where its simulated flow is influenced by the water flow requirement of 15 m^3 s^{-1} (39 Mm^3 $month^{-1}$) needed to meet the firm energy requirements at the HEP. Both gauging stations are located downstream of Kirua swamp.



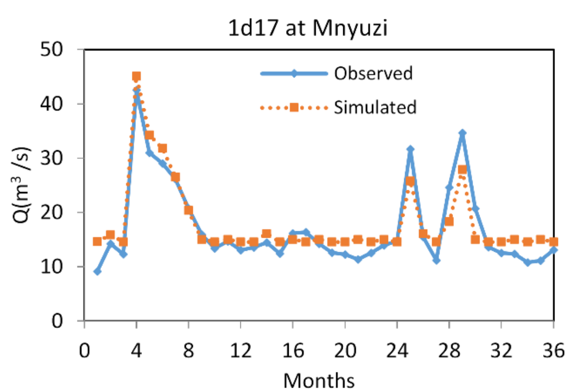


Fig. S2. Observed and simulated discharge at a) gauge 1d14 at Korogwe, b) gauge 1d17 at Mnyuzi for the period 2008 – 2010.

The lower performance of the model to simulate discharge compared to reservoir water level can partially be attributed to uncertainties in discharge measurements. Errors in estimating water losses from Kirua swamp and actual water abstractions especially during low flows may have affected the model performance.

The simulated and historical annual energy generation (firm, 5-yr and long-term) for each of the hydropower stations are provided and compared in Fig. S3. The long term historical energy production was available for the period 1985 - 2006 for NyM and Hale HEP and 1995 to 2006 for the NPF HEP (PBWO/IUCN 2009). The 5-year historical hydropower was for the period 2002 - 2006 for all HEPs.

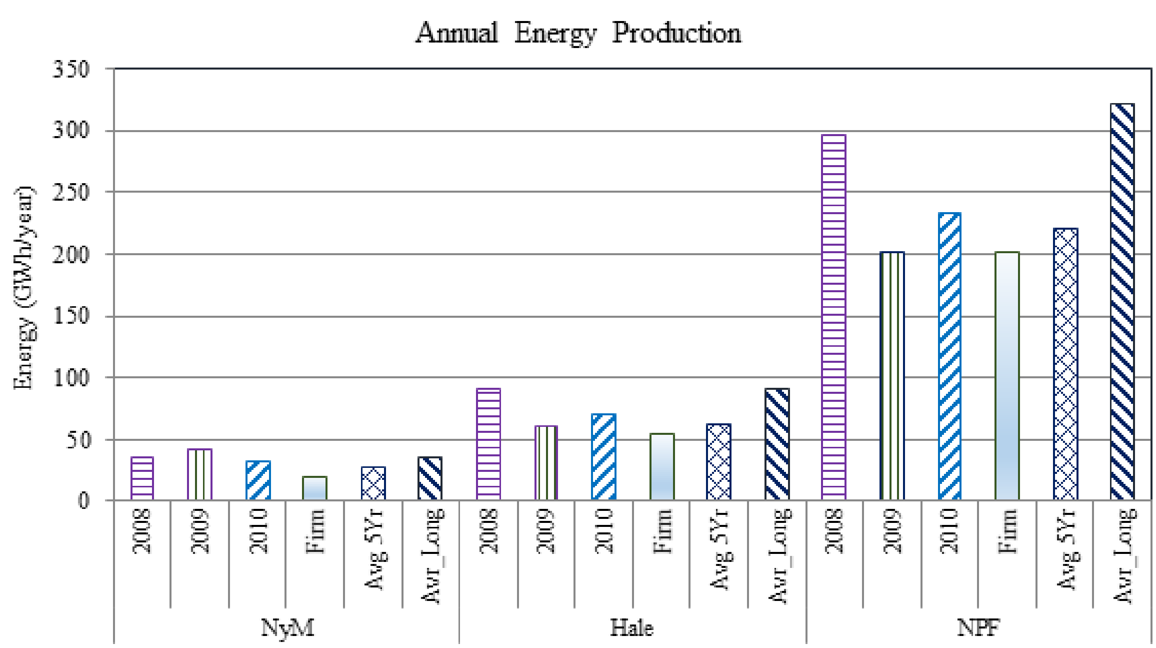


Fig. S3. Simulated annual energy production compared with firm, avg. 5 yr (2002 - 2006) and long term avg. for NyM, Hale and NPF Hydropower stations

The simulated hydropower production is higher than the firm energy requirements for the HEPs, which is expected. The average long term hydropower is higher than both 5-yr and the simulated hydropower. This may be caused by declining water inflows into the lower Pangani hydro-system due to recent increased water use by agriculture (PBWO/IUCN 2007). The simulated hydropower for NyM reservoir shows small variance due to the regulated flow at NyM reservoir. High hydropower generation is realized in the dry year 2009 in NyM HEP due to increased outflow from NyM reservoir, an increase that is explained by the objective function of meeting the firm hydropower production by the large capacity HEPs downstream, and a subsequent lowering of the water level in NyM reservoir. In Hale and NPF HEPs, the hydropower production is higher in 2008 (wet year) largely due to higher (unregulated) discharge from Mkomazi and Luengera tributaries. The variability in energy production in 2008 (wet), 2009 (dry) and 2010 (average) years is also due to uncontrolled inflows from Mkomazi and Luengera tributaries. There is general consistency between the average hydropower productions over the simulated period (2008 - 2010) with the 5-yr historical data (2002 - 2006). There is also consistency of the intra-seasonal trend in the hydropower production for the run-of-river Hale and NPF HEPs.

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