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Water conservation can reduce future water-energy-food-environment trade-offs in a medium-sized African river basin

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ABSTRACT

The need for achieving efficient and sustainable use of water resources is pressing, however, this often requires better understanding of the potential of water conservation, taking into account the impact on return flows, and the costs in relation to sectoral benefits. Using modelling and limited observational data we explore the costs and potential water savings of 24 combinations of water conservation measures in the Rufiji basin, Tanzania. We compare these costs with estimates of the value such water savings could generate from water use in three important economic sectors; agriculture, energy and downstream ecosystems with high tourism potential. The cost of water conservation measures (median: 0.07 USD m^{-3}) is found to be: higher than the value of most uses of water for agriculture (growing crops in expanded irrigation sites) and the median value for hydropower generation (from a new mega dam currently under construction); and lower than the ecosystem value. Nevertheless, under our modelling assumptions, the volume of additional water required to supply planned irrigation expansion in the basin could be reduced by 1.5 BCM using water conservation methods that would be financially viable, given the value of competing uses of water. Water savings of this magnitude would reduce potential trade-offs between use of water for hydropower and ecosystem services, by allowing peak environmental flow releases even in dry years, and without reducing firm energy generation. This methodology is transferable and relevant for producing realistic assessments of the financial incentives for long-term sustainable water use in agriculture, given incentives for other uses. With most reservoirs now being built for multiple purposes improved understanding of trade-offs between different sectors and functions is needed.

1. Introduction

Many river basins in the Global South are undergoing rapid development with major implications for the interdependent water-energy-food-environment nexus sectors. Strong intra- and inter-annual variability in precipitation - amplified through river basin hydrology – and uncertainty about the direction and magnitude of ongoing climate change further complicates development planning, stretching climate risk profiles for irrigated agriculture, hydropower and environmental flow performance indicators (Kolusu et al., 2021; Siderius et al., 2021b).

Yet, development is not always well aligned between sectors (Pardoe, 2018). Minimising the impact of distributed upstream development and increased water utilisation on downstream infrastructure such as hydropower plants, or on vital ecosystems, is a major challenge that arises from this situation. Many demand-side measures are widely proposed as part of adaptive management portfolios to address these concerns, such as more efficient irrigation systems (Gleick, 2002; Jägermeyr et al., 2015), with on-farm management practices promoted for their cost-effectiveness (Addams et al., 2009). Basin-scale benefits of these efficiency-oriented measures, however, often turn out lower than anticipated (Grafton et al., 2018; Lankford, 2012; Perry, 2007; Scott et al., 2014; van Halsema and Vincent, 2012), with savings different to what was promoted or expected (van der Kooij et al., 2013; Venot et al., 2017). Upstream increases in efficiencies also tend to reduce the return flows that downstream farmers rely on. And in practice, farmers may expand or intensify production and, as a result, consume more water when moving to more efficient types of irrigation like drip or sprinkler, thereby reducing rather than increasing downstream supply. The UN's

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Food and Agriculture Organization, FAO, therefore makes a distinction between 'real' water savings and 'apparent' water savings (Van Opstal et al., 2021). Real water savings are any reductions in water consumption and non-recoverable return flows, water that would otherwise be lost to evaporation, rather than reductions in water withdrawn from a river or applied to a field.

The Rufiji River basin in Tanzania is experiencing rapid development. It produces roughly half of Tanzania's river flow, supplies water for 4.5 million people and generates 80% of the country's hydropower (almost 50% of the total combined national hydro-thermal power capacity) (WREM International, 2015b). Construction of the Julius Nyerere Hydropower Project (JNHPP) is underway (started in 2019), located on the main stem of the Rufiji (Fig. 1). At 2115 MW potential hydropower capacity the JNHPP is the second largest hydropower plant in Africa under construction and will double Tanzania's hydropower capacity.

The Rufiji River basin also contains most of an area earmarked for ambitious agricultural expansion, the Southern Agricultural Growth Corridor of Tanzania (SAGCOT, Fig. 1A). SAGCOT comprises several concentrated areas of activity (clusters) and it aims to attract domestic and foreign investment in agricultural value chains to promote economic growth (Milder et al., 2012). Increased agricultural productivity, particularly through increased irrigation, is part of SAGCOT initiative and sustainable water resource management is viewed as key to its success. However, while there is high development potential, many decisions involve, among other things, trade-offs between the water, energy, agriculture and conservation/tourism sectors. Critical among these is the cumulative effect of abstractions to support expansion of irrigation upstream through formal large-scale schemes and informal small-scale expansion (e.g. the Rufiji River basin master plan aims to an increase irrigation from 110,000 ha to approximately 400,000 ha by 2035 (WREM International, 2015a). Simulations show that the higher estimates of upstream abstractions would constrain the reliability and amount of hydropower production (Geressu et al., 2020). While such an increase seems unlikely, given current low rates of expansion and historic performance in planned large-scale irrigation sub-Sahara Africa (Higginbottom et al., 2021), at the same time, local irrigation initiatives and farmer-led irrigation expansion are widely observed in sub-Saharan Africa, though often under-reported or under–recognised (Venot et al., 2021).

An estimated 2.4 billion cubic metres of water (BCM) is currently abstracted in the Rufiji River basin per year, primarily for irrigation. This is projected to increase more than threefold with the planned expansion of irrigation (WREM International, 2015b), an amount equalling more than 33% of runoff in low flow years (Rufiji mean annual discharge is ~30 BCM, over 1981–2010, and as low as 20 BCM in the driest years). Precipitation in the Rufiji River basin is highly seasonal with a mix of uni- and bi-modal maxima together with a complex hydrology including several major wetland systems (Siderius et al., 2021b).

Currently, unlined canals and lack of gates make it difficult to control irrigation water flows and unlevelled fields cause uneven distribution of water (Mdemu et al., 2017). While some of the drainage losses are reused by smallholder farmers surrounding larger irrigation schemes, or further downstream, a significant but unquantified proportion of water withdrawals is lost to evaporation. Through various land management and irrigation practices part of these losses might be reduced and some possible nexus sector trade-offs, e.g. the impact of the JNHPP reservoir on the Rufiji's downstream delta ecosystem, could potentially be mitigated (Geressu et al., 2020). A better understanding of their cumulative

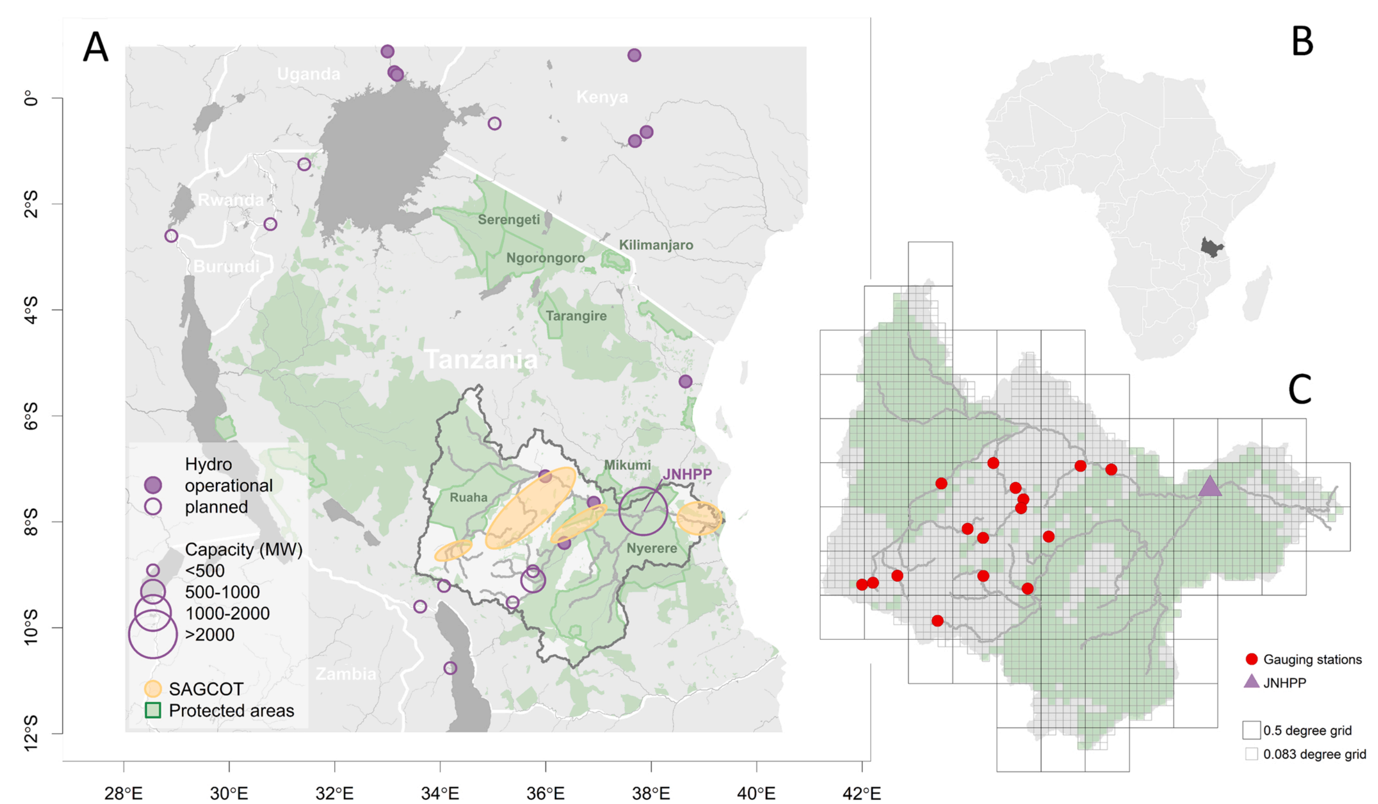

Fig. 1. A Rufiji River basin in Tanzania (in lighter grey with dark outline), with operational and planned hydropower sites, agricultural growth corridor (SAGCOT) areas and protected nature areas with National Park or World Heritage Sites outlined, with the Serengeti, Kilimanjaro, and Tarangire National Parks and the Ngorongoro conservation area forming part of the 'northern circuit' for tourism, and Ruaha, Mikumi and Nyerere National Parks promoted as a high potential 'southern circuit'; B location of the basin in Africa, and; C model grid (0.083 degree resolution for the precipitation input and hydrological and crop growth calculations, and 0.5 degree for the radiation and temperature forcing), with locations of gauging stations used for calibration of model parameters as described in Siderius et al. (2018).

potential, taking into account the impact on return flows, and the costs in relation to sectoral benefits that recognise all users is required to understand and quantify trade-offs to support greater coordination within the basin (Kadigi et al., 2008).

Assessments of the value of environmental flows and resulting ecosystem services are often lacking. The benefits are diverse and hard to quantify and their translation into volumes constrained by complex relationships between value (depreciation) and (lack of) space- and time-specific environmental flow conditions. Environmental flows in the Rufiji River basin exhibit strong threshold characteristics, with ecosystem functioning highly dependent on biennial peak flows that regenerate a coastal delta lake ecosystem with high wildlife densities (Duvail et al., 2014; Hamerlynck et al., 2011). Yet, these peak flows are very sensitive to reservoir operations such as those that would result from completion of the JNHPP.

With most reservoirs today being built for multiple purposes, it is important for policymakers to appreciate and plan for growing trade-offs between key functions (Zeng et al., 2017) and to recognise the range of water users at different scales in the basin. Improved understanding of the value of water in its different uses can contribute to informed debate on water management and allocation, identifying the basis for making 'agreeable' trade-offs. We address this goal by exploring the financial costs of different water conservation measures under an ambitious plan for irrigation expansion, using an improved application of the cost curve methodology (Siderius et al., 2021a). We demonstrate how the methodology can be combined with water accounting and expand its use beyond agriculture by adding a comparison with the value of water for different sectors, to show its potential for aiding multi-sector decision-making. We first derive cost curves (i.e. curves showing increasing marginal costs of water savings) and then compare them with estimates of the value of water for the agriculture, energy, and environment sectors, to understand the financial feasibility of water conservation within a rapidly developing river basin. We also examine the extent to which water conservation can help reduce the sensitivity of ecosystem services to reservoir operations; by considering the volume of water savings at which the biennial frequency of peak flows (a key environmental flow indicator) can be maintained, without negatively affecting firm monthly hydropower production, assuming full development of ambitious large-scale irrigation plans.

2. Methodology

In overview, we utilise an established crop-hydrology model adjusted to the Rufiji River basin (Siderius et al., 2018) with additional validation of local crop production. Government plans for irrigation expansion and their consequences for water use are used to calculate the potential water savings associated with 24 combinations of water conservation measures. Hydropower yield from the JNHPP is modelled as a v-shaped reservoir (Siderius et al., 2021b). To assess how much water conservation can help reduce water-energy-food-environment sector trade-offs, the cost of measures are compared with estimates of the value of water for agriculture, environment and hydropower, derived from publicly available literature (Fig. 2). A cost curve combines the marginal costs of measures – in the case of water, the cost of providing one additional cubic metre of water - with the expected total amount of extra water a measure can conserve, and ranks these measures from low to high marginal costs. Cost curves provide a method to identify the most cost-effective water conservation measures to improve cost-based decision-making, particularly in situations approaching water scarcity, and to illustrate trade-offs and consequences of decisions (Addams et al., 2009; Siderius et al., 2021a).

2.1. Simulation of crop production, hydropower yield and environmental flows

To simulate the building blocks for our analysis (that is, gridded irrigation water withdrawn and applied, and return flows and resulting additional crop production), we use an adjusted, basin-specific, calibrated version of the LPJmL model (Siderius et al., 2018), a model that simulates a coupled hydrology and carbon cycle, which makes it a suitable tool to study the interactions between water availability and food production (Gerten et al., 2011). Daily irrigation demand for an irrigated crop in a cell is calculated as the minimum amount of water needed to fill the soil to field capacity and the amount needed to fulfil

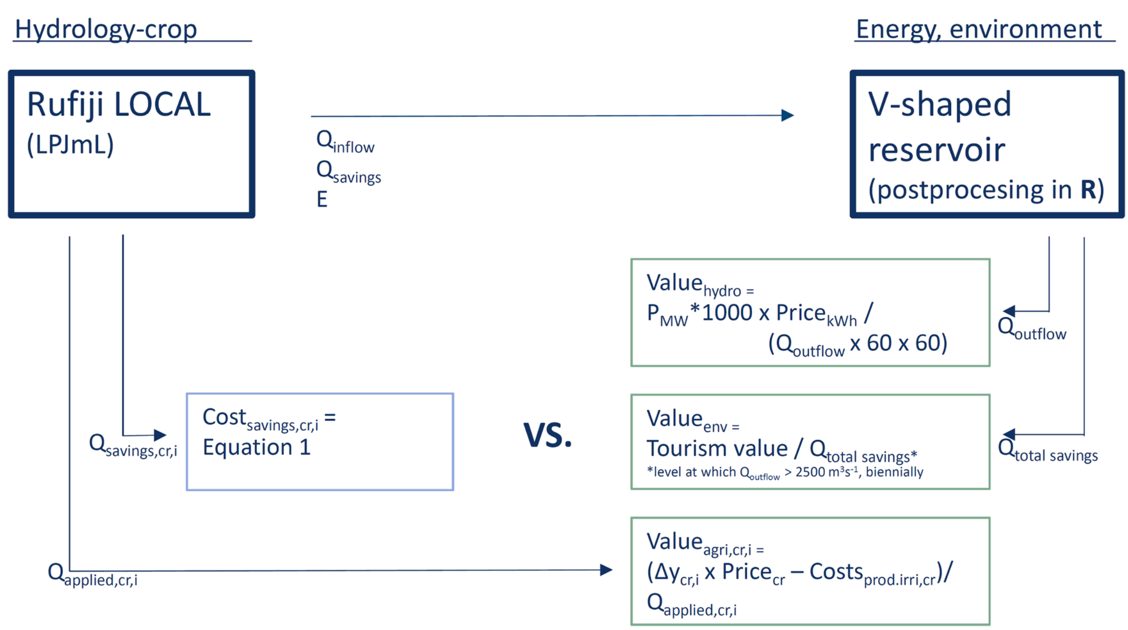

Fig. 2. Summary flowchart of method, with Q_{inflow} as volume of flow (m^3 s^{-1}) into the JNHPP, $Q_{savings}$ the cumulative upstream 'real' water savings, evapotranspiration, E, (to estimate evaporation losses from the reservoir surface, with surface area a function of height), P_{MW} the design capacity of the hydropower station (in MW) $Price_{kW\,h}$ the kW h price in USD kW h^{-1} and $Q_{outflow}$ the outflow through the turbines (with a maximum of 2061 m^3 s^{-1}), with $\Delta Y_{cr,i}$ the difference in irrigated and rainfed crop yield, per measure combination, $Price_{cr}$ the price of crops in USD ton^{-1} and $Costs_{prod.irri,cr}$ the additional production costs attributed to irrigation.

the atmospheric evaporative demand. Subsequently, the withdrawal demand is calculated by accounting for losses during conveyance, distribution and application of water, depending on the type of irrigation system installed (surface, sprinkler or drip) and the soil type of the irrigated cell (Jägermeyr et al., 2015). The model tracks the proportion of losses that return back to the river system. Real water savings are derived by correcting the difference in water withdrawn for a change in return flows and, thus, only represent the change in consumption and non-recoverable return flows.

Rain-fed and irrigated crop growth for 12 crops (including wheat, rice, cotton and sugarcane) is based on daily assimilation of carbon. In cases of crop water stress, the allocation of carbon to the storage organs is decreased, leading to reduced yields. Crops are harvested when either maturity or the maximum number of growing days is reached (Bondeau et al., 2007; Fader et al., 2010). Yields for the most important food crops and sugarcane and cotton have been calibrated against subnational agricultural statistics (Government of Tanzania, 2017a,b) by adjusting a management factor in the LPJmL model that influences maximum leaf area index, maximum harvest index and a parameter to scale leaf-level biomass production. Yields differ across the basin, due to differences in climatic and soil conditions, and access to irrigation.

For 2035, the National Irrigation Commission under the framing of the National Irrigation Masterplan proposes a very ambitious increase in irrigation from 111,000 ha of irrigation in 2010 to 400,000 ha in the basin (WREM International, 2015a,b). About a third of this expansion is explicitly defined in the model as four large planned irrigation schemes: 23,000 ha of sugarcane in the Kilombero sub-catchment (associated with an existing ILLOVO plantation); 18,000 ha for various crops earmarked for expansion in USAID feasibility studies (CDM Smith, 2016), 6260 ha rice in the Usangu sub catchment and 69,000 ha downstream of the JNHPP. The other two-thirds of expansion consists mostly of small- and medium-sized schemes, including estimates of informal 'farmer-led' irrigation expansion, and is spatially allocated using the following rules: 1. No expansion in game reserves or national parks; 2. Prioritising SAGCOT districts; and 3. Prioritising cells with existing irrigated area (based on MIRCA2000, a global dataset of cropping patterns of 26 major crop types for the year 2000 (Portmann et al., 2010)) and then cells with existing agriculture (assuming these to be most suitable due to existing infrastructure), and restricting total cropped area to 90% of cell area. We exclude the area downstream of the JNHPP from this analysis as we assume it does not directly influence reservoir operation and water availability for other sectors, and so our assessment focusses on an expansion of irrigated area to 292,000 ha, ~75% of the total planned irrigated area in the basin. In the Rufiji River basin there are three major irrigated crops simulated; rice, maize, and sugarcane. A range of other crops, such as onions and tomatoes and cassava are irrigated to a lesser extent and we cluster them under an 'other irrigated' crop class using the cassava parameterisation, the third most popular food crop in the basin. A distinction between dry and wet season specific irrigation expansion was made (with rice as the wet season crop, and dry season expansion targeted as 'other crops').

To calculate hydropower yield, the JNHPP was modelled in the programme R (https://www.r-project.org) as a v-shaped reservoir, using simulated LPJmL flows as input, with firm energy production (the minimum amount of energy that can be produced, typically in e.g. 90% or 95% of all months, reflecting hydrological variability), a function of head (height difference between the water level at intake minus the level at discharge), turbine efficiency (up to 95% efficiency for large Taylor Francis turbines commonly used) and outflow through the turbines. We derived the basic characteristics of the reservoir and hydropower plant from earlier planning reports (UNDP/World Bank, 1984) and national and basin studies that often quote the 2013 planning documents of Brazilian construction firm Odebrecht and/or the Power System Master Plans of the Tanzanian Ministry of Energy and Minerals (Government of Tanzania, 2012, 2016; WREM International, 2015a,b; WWF International, 2017). Nine turbines are expected to deliver ~2100 MW capacity, which - if run constantly at maximum outflow and head - would deliver over 18,000 GW h per year, but the JNHPP is expected to operate on a lower capacity on average. With detailed information on demand fluctuations and planned operating rules lacking, we base our analysis on the flow needed to maintain reported firm energy production, ~6000 GW h per year (Hartmann, 2019), which would be achieved by running the turbines at a third of total turbine capacity at maximum head. Energy production decreases linearly with lower head; at the lowest reservoir level, at dead storage, this results in a reduction of approximately 22% at constant outflow. Hence, to maintain firm energy production, an increase in flow through the turbines of similar magnitude is required to offset this potential reduction. Due to lack of information we do not consider hourly or daily to monthly fluctuations in supply to meet peak demands.

Environmental flows downstream of the JNHPP are characterised by the need for regular, biennial, seasonal peak flow of 2500 m^3 s^{-1} or more, to create bank overflows that replenish the interconnected delta lakes and surrounding wetlands (Duvail et al., 2014). The development of the JNHPP threatens to disrupt the biennial peak flows regenerating the lake ecosystem on which much wildlife depends (Duvail et al., 2014; Hamerlynck et al., 2011). In our model, such a monthly flow is released if the reservoir is: i. at capacity and inflow that month exceeds 2500 m^3 s^{-1} (plus evaporative losses from the lake surface); ii. at capacity in May and with runoff in the previous month above 1500 m^3 s^{-1}, indicating the likelihood of a sufficient wet season inflow to fill up the reservoir, or iii. if there has not been a peak flow of above 2500 m^3 s^{-1} in the previous wet season and months up to May, and the reservoir is at least still 2/3rd full. With little or no inflow, a peak release of 2500 m^3 s^{-1} during a month would require about 25% of the reservoir's capacity leaving just about enough volume to maintain firm energy production until the next rainy season. We used a 30 year historic climate data series (1981–2010) derived from the CHIRPS gridded global precipitation dataset (Funk et al., 2015).

2.2. Water conservation measures

The types of water conservation measures that might be appropriate (or under consideration) in the Rufiji River basin relate to the type of irrigation system, land management and in-situ water harvesting (Table 1). These measures represent the major pathways through which irrigation water can be conserved and reallocated: capture more rainfall to reduce the amount of irrigation required; reduce evaporative losses from the soil; and reduce evaporative losses from the irrigation supply system. For this analysis the parameterisation of field level measures was based on general values used in Jägermeyr et al. (2016). Furthermore, in Tanzania, formal irrigation infrastructure is widely in need of rehabilitation and generally has efficiencies lower than many parts of the world (Government of Tanzania, 2018), although in situ observations are sparse to confirm this. We therefore assumed that the many unlined canals and older infrastructure in the basin would have a reduced canal conveyance efficiency in the baseline situation (by 20% points), but added improvement to best practice standards as an option.

The type of irrigation system strongly determines the efficiency of water use, with differences in field application and transport to the field resulting in varying amounts of productive water consumption, non-productive losses and return flows (Irmak et al., 2011; Jägermeyr et al., 2015). Surface irrigation, whereby the field is flooded to a certain depth with each irrigation application with water supplied through open channels, is the default system in the Rufiji. Flooding requires an additional amount of water to distribute irrigation water uniformly. A distribution uniformity ('DU') parameter is used to scale this additional amount of water (Jägermeyr et al., 2015). A value of 1.15 for surface irrigation (Table 1) means more than a doubling of the irrigation amount needed to replenish the soil. Sprinkler irrigation applies water closer to the plant and distributes it more evenly leading to lower application losses. In drip systems application water is applied right into the

Table 1
Selection of water (and soil) management measures evaluated in this study and their annualised cost. See SI for an overview of literature on costs of water conservation measures.

Water conservation measure	*Components*	*Parameterisation*	*Annualised cost (2018 USD ha^{-1}year^{-1})*	*References to cost estimate*
Irrigation system field application	Shift to, sprinkler, drip	**Sprinkler**: conveyance losses 25%, DU 0.55	305	Paul (1997)
		Drip: conveyance losses 25%, DU 0.05	547	Phocaides (2007)
Land management	Mulching (organic residues, plastic films), conservation tillage	Soil evaporation during growing season reduced by 25%	123	Anane et al. (2020)
In-situ water harvesting	Pitting, terracing, mulching	Infiltration parameter, as in Jägermeyr et al. (2016), multiplied by two	49	Bizoza and De Graaff (2012)
Conveyance system upgrade	Lining, covering water storage, improved distribution systems	Reduction of conveyance losses by 20% points	102	Government of Tanzania (2018)

DU = distribution uniformity, (Jägermeyr et al., 2015).

rootzone of the plant, eliminating leaf interception evaporation losses and further reducing soil evaporation. We assumed sprinkler and drip irrigation techniques to be suitable for all irrigated crops, including rice and sugarcane.

While canal conveyance losses for well maintained and managed irrigation systems are estimated between 20% and 30%, depending on the soil type, they can be almost double this in older systems or those lacking maintenance (Brouwer et al., 1989). Canal conveyance losses in the Rufiji basin were initially set at 40–50%, depending on soil type. Sprinkler irrigation uses pressurised water transport through pipes, with conveyance losses in well designed and operated systems estimated at only 5% (Brouwer et al., 1989), but as high as 25% in some systems (Battikhi and Abu-Hammad, 1994; Bos and Nugteren, 1990). This is not necessarily due to a lack of maintenance; losses can occur before the control station, or in open storage reservoirs. In rehabilitated drip systems in Tanzania, losses of 14% were reported (Government of Tanzania, 2018). To reflect this difference, we distinguish in our drip and sprinkler water conservation measures between those with 'baseline' conveyance losses of 25% and an upgraded option with losses at only 5% but against higher costs.

Land management techniques such as mulching (covering the soil with crop residues or plastic film) reduce non-beneficial soil evaporation. Taking into account current practices in the Rufiji where mainly crop residues are used (Mahoo et al., 2007), we have used the low-end estimate of Jägermeyr et al. (2016) which assumes this measure reduces soil evaporation by 25%. In-situ water harvesting relates to techniques to increase on field infiltration such as pitting and terracing as well as mulching. This increases soil water content and reduces the need for additional irrigation water. Infiltration, a non-linear process, approximately doubles at higher soil moisture contents when applying this type of measure.

Combining these measures leads to a total of 24 unique combinations of water conservation measures on irrigated land. We assume that measures like drip or sprinkler have not been implemented to any great extent in the Rufiji as such methods are yet to be applied at large scale (over 90% of irrigation in Tanzania is of the gravity type (Government of Tanzania, 2018)). Minor exceptions we are aware of include the Kapunga Irrigation scheme (Great Ruaha subcatchment) and Illovo sugarcane plantation (Kilombero subcatchment) where sprinkler irrigation has been in operation in recent years.

2.3. Water conservation cost curves

Estimates for annualised, area-based costs of various measures were derived from literature (Table 2 and SI). Costs vary greatly, with drip the most expensive method and mulching (using locally sourced organic materials) the cheapest per ha. Costs for a combination of measures were derived by adding up each individual cost. Reported figures mainly concern hardware costs and exclude the cost of training and outreach, which can be considerable, depending on existing farmer knowledge and capacities of agricultural extension services (Stirzaker et al., 2014).

Costs expressed per hectare were converted into annualised capital costs and then into volumetric costs using simulated irrigation amounts per hectare. As a result, while cost per hectare for a particular measure is assumed constant, volumetric costs vary spatially and per crop, depending on local climate and soil conditions. To derive marginal costs, we iteratively rank per crop and per cell all combinations of measures, from low to high marginal volumetric cost, deselecting those options that do not conserve additional water.

$$Cmarg_{c,i} = \frac{(Q_{cr,i-1} * C_{cr,i-1}) - (Q_{cr,i} * C_{cr,i})}{(Q_{cr,i-1}) - (Q_{cr,i})} \quad (1)$$

With

$$C_{cr,i} = Cinv_{cr,i} - \quad Cm3 * \frac{Qapplied_{cr,i}}{Q_{cr,i}}$$

where *Cmarg* is the marginal costs (USD m^{-3}) for crop *cr* and water conservation option *i,* based on the volumetric cost, *C*, with *Q* the volume of 'real' water savings and with $C_{i-1}(Q_{i-1})$ the volumetric cost (volume saved) of the previous best option. *C* is based on the volumetric investment costs, *Cinv*, and the operating cost for a farmer to apply a cubic metre of water, *Cm3*, in the Rufiji basin set at 0.01 USD m^{-3} based on the electricity costs to create a pressure of head of 50 m with a pump of standard efficiency of 55%, required to irrigate via sprinkler or drip. We assumed a standard cost of 0.01 USD m^{-3} would equally cover the continuous maintenance and operation costs that come with surface irrigation. Farmers would forego these costs in cases where they apply

Table 2
Agricultural statistics for four crops (2018 USD values).

Crop	$Yield_{observed}$[a] mean	$Yield_{simulated}$ mean	irrigated	Cost USD/ha	Price USD/ton	Break even yield ton/ha	Reference for cost of production estimate
Rice	1.9	2.5	2.7	513	386	1.3	Wilson and Lewis (2015a)
Maize	1.4	1.8	2.8	486	232	2.1	Wilson and Lewis (2015b)
Sugarcane	68	73	73	1980	39	51	Mwasinga (2018)
Other[b]	4.3	4.2	9.6	512	175	2.9	Abass et al. (2013)

[a] Based on district statistics average of all districts within the Rufiji basin. Source: Tanzanian Ministry of agriculture.
[b] Cassava as proxy.

water conservation measures, hence the negative sign.

We correct for impacts on irrigation return flows, whereby Q is the savings in irrigation water withdrawn minus any reduction in surface runoff, soil drainage or canal conveyance return flows which downstream users might rely on. Not only does this reduce the expected amount of water saved, it also increases the volumetric investment costs thereby making measures that reduce return flows less attractive (as compared to those that reduce mainly evaporative losses). This does not apply to operating costs, since the farmer foregoes these costs on the reduced amount applied on their field. To account for this in our marginal costs, we adjust the volumetric operational costs (*Cm3*) by multiplying them with the fraction of applied over real water savings.

2.4. Valuing water

We compare the marginal cost of water conservation measures against the value that water could potentially generate elsewhere in agriculture, and in two other sectors; hydropower and ecosystem services related to tourism and fisheries.

The marginal value of irrigation water is determined with the residual value of irrigation (in USD m^{-3}), at the margin of what can be produced using rainfed methods. The residual value represents the value of a marginal product of a non-priced input (Young, 2005) which, in the case of irrigation water, is derived by subtracting all non-water related estimated costs of production from the total value of output and then dividing this residual by the amount of water applied. We rely on the same hydrological and crop production simulations that underpin the cost estimates but here use the volume of irrigation applied and the additional amount of crop that is produced with this amount of irrigation water, multiplied by the farm gate price.

Annual prices of crop produce for the period 2000–2018 were taken from FAOSTAT, and corrected for inflation to 2018 price levels. National-level, crop-based weighted averages were calculated, with weights assigned based on the years before present, thereby giving higher importance to more recent price levels while at the same time accounting for historic price fluctuations. Basin specific sugarcane prices (Mwasinga, 2018) were used as these were unavailable in FAOSTAT. Costs of production were taken from field surveys in the basin (Table 2). Profit margins are low at the mean observed and simulated maize yields, which is mainly grown for home consumption, below the break-even level of productivity. Sugarcane outgrowers, smallholder farmers who sell their produce to the nearby estate that owns a sugar factory, achieve much lower yields (27–30 ton ha^{-1}; (Chanzi, 2016; Siima et al., 2012)) than the large estates which dominate the average and apply more irrigation.

The value of hydropower depends on many direct and indirect benefits to the economy and society, some of which may materialise long into the future and are therefore difficult to quantify. One alternative is to assume current tariffs represent the value of electricity. Another approach, as used here, is to assume that the costs of constructing and operating the infrastructure, the Levelized Cost of Electricity (LCOE, all costs of construction and operation over the lifetime of the infrastructure) should at least equal the value that a hydropower project generates. To do this we used a kW h cost price of 0.137 USD from Tanzania's national energy master plan based on an estimate of marginal cost of supply (for production and transport) (Government of Tanzania, 2016). Fixed costs per kW h were converted into a volumetric cost using the simulated reservoir outflow required to maintain firm energy production, which is dependent on reservoir levels, at daily time steps.

While valuations of ecosystem services in Africa are limited compared to other continents, studies on water related ecosystem services form a much higher proportion of all studies in Africa (Pettinotti et al., 2018). Here, we assign an ecosystem value to water using its essential role in wildlife-based tourism, a major contributor to GDP in Tanzania, of foreign currency, and of employment (Cunningham et al., 2015; World Bank Group, 2015). Most tourists visit the national parks in the North of the country, the Serengeti and Kilimanjaro, leading to overcrowding in what is called the 'northern circuit', while the potential of the southern parks, including two in the Rufiji River basin (Ruaha National Park (RNP) and Nyerere National Park (NNP, part of the former Selous Game Reserve), Fig. 2), is still underexploited (World Bank Group, 2015). The World Bank estimates that attracting more people to these parks could boost annual GDP by almost 300 million USD (corrected for inflation to 2018), provided that two water-related potential barriers could be overcome; water scarcity in the dry season in the RNP, and bad connectivity with nearby parks with the NNP, situated between the RNP and major urban centres such as Dar es Salaam, considered a vital link (World Bank Group, 2015). Starting from an expected trade-off, with prioritisation of firm energy likely to affect flow variability downstream of the JNHPP (Duvail et al., 2014; Geressu et al., 2020) and thereby the viability of the NNP as a high-value tourism destination, the annual potential tourism revenues of 300 million USD are attributed to the amount of water conservation needed for the JNHPP to produce both firm energy, and maintain biennial peak flows above 2500 $m^3 s^{-1}$.

3. Results

3.1. Potential of water conservation

The modelled potential to reduce both irrigation withdrawal and net irrigation after correcting for the impact on irrigation return flows is high in the Rufiji basin due to the large volumes of non-beneficial consumptive losses both on field and in the distribution system assumed in the baseline simulation conditions. Of the more than 2000 mm of irrigation water that is withdrawn in the canal fed systems, only a small fraction contributes to crop transpiration (Fig. 3A). About half is lost in the distribution system, of which half represents permanent losses through evaporation, while the other half is either returned to the river or reused. Of the amount of water actually applied (1162 mm), 40% is consumed beneficially and non-beneficially, while the other 60% is unaccounted for and might return back into the river system at some point in time. Net irrigation, withdrawal minus return flows, is about 1000 mm a year.

Implementing water conservation measures reduces both consumptive losses and return flows. In the most effective simulated condition (from a water conservation point of view) (Fig. 3B), with irrigation provided by sprinkler and with evaporation reduction, conveyance losses and soil return flows are almost eliminated. Net irrigation is only about 400 mm $year^{-1}$ (supplementing rainfall of 907 mm $year^{-1}$ of which 727 mm falls within the growing period) while maintaining transpiration and, thus, yield. Real water savings, accounting for changes in return flows, amount to a difference in net irrigation of about 600 mm $year^{-1}$. Infiltration enhancement has a negligible impact under all three irrigation systems, with a small reduction in irrigation applied, in order of tens of mm, matched by a similar reduction in (surface) runoff.

Through a combination of various water conservation measures, the ratio of non-beneficial consumption to total consumption (RNC) can be reduced from 72% to as lows as 23% (Table 3). High conveyance efficiencies for 'improved' sprinkler and drip systems with pressurised supply have conveyance efficiencies of close to 100% which, combined with efficiencies at field level, leads to overall efficiency of up to 60%. A strong reduction in withdrawal and net irrigation, comparable to some of the sprinkler options, is also possible within canal-fed irrigation systems, when irrigation application to the field is reduced, which limits the supply through the canal system and evaporative losses therein. Improved conveyance can further lower these evaporative losses. Accounting for changes in return flows preserves the total amount of flow available to downstream uses, but flow patterns will be shifted towards more flow retained in the river system and less routed via the canal, soil and the drainage system away from the river. Runoff will be faster, with

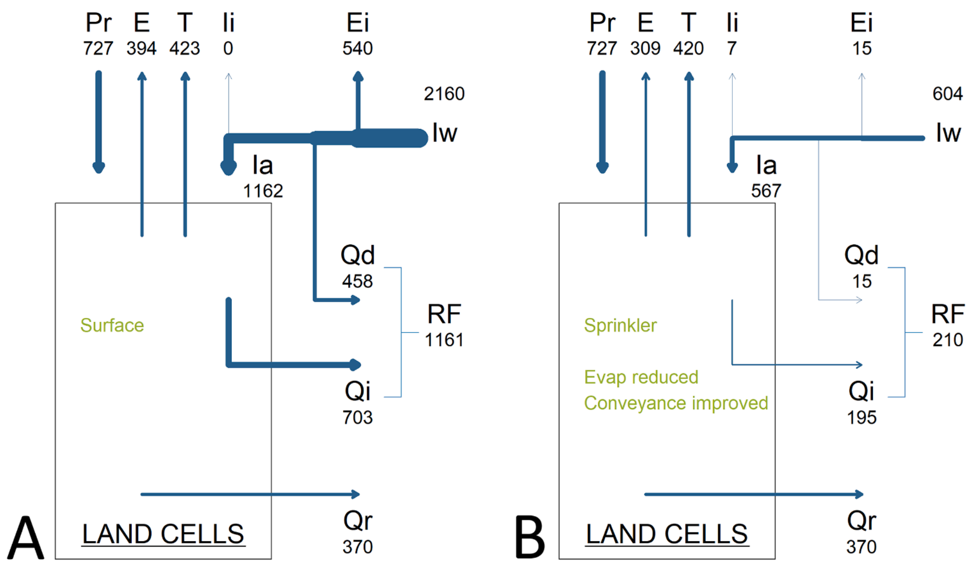

Fig. 3. Average water balance of all irrigated crops in the Rufiji River basin (in mm per year) for the baseline without any measures (A) and with one of the most cost-effective combination of measures (B). With irrigation withdrawal (Iw), canal evaporation (Ie), canal seepage losses (Qd), irrigation applied (Ia), and irrigation interception losses (Ii), and with precipitation minus interception (Pr), evaporation (E), crop transpiration (T), irrigation return flows through the soil column (Qi) and other runoff (Qr, consisting of surface runoff, lateral runoff and seepage other than attributed to irrigation), and total return flows (RF).

Table 3
Impact of combinations of water conservation measures on irrigation withdrawal (Iw) and return flows (Qd) and conveyance (Ec), field (Ef) and overall (Eb) efficiency. RNC is the ratio of non-beneficial consumption to total consumption.

Characteristics				Water balance (mm)		Efficiencies			
Application type	Infiltration enhancement	Evaporation reduction	Conveyance improvement	Net impact	RNC	Ec	Ef	Eb	Ei
Surface				0	72	0.54	0.23	0.12	0.45
Surface	+			25	72	0.54	0.24	0.13	0.45
Surface		+		156	70	0.54	0.25	0.14	0.44
Surface	+	+		179	69	0.54	0.26	0.14	0.45
Surface			+	304	59	0.74	0.23	0.17	0.42
Surface	+		+	311	59	0.74	0.24	0.18	0.43
Surface		+	+	419	55	0.74	0.25	0.19	0.42
Sprinkler	+			424	51	0.75	0.37	0.28	0.58
Surface	+	+	+	426	55	0.74	0.26	0.19	0.42
Sprinkler				428	51	0.75	0.38	0.29	0.59
Sprinkler	+		+	514	41	0.95	0.37	0.36	0.60
Sprinkler			+	522	41	0.95	0.38	0.37	0.61
Sprinkler	+	+		523	47	0.75	0.41	0.30	0.57
Sprinkler		+		525	46	0.75	0.42	0.31	0.58
Drip	+			544	38	0.75	0.62	0.47	0.76
Drip				554	38	0.75	0.64	0.48	0.77
Drip	+		+	587	28	0.95	0.62	0.59	0.83
Drip			+	600	28	0.95	0.64	0.60	0.85
Sprinkler	+	+	+	601	35	0.95	0.41	0.39	0.59
Sprinkler		+	+	606	35	0.95	0.42	0.40	0.61
Drip	+	+		617	34	0.75	0.65	0.49	0.75
Drip		+		623	34	0.75	0.67	0.5	0.76
Drip	+	+	+	655	23	0.95	0.65	0.62	0.81
Drip		+	+	663	23	0.95	0.67	0.64	0.83

earlier availability to other users (Lankford, 2012).

3.2. Cost curve for water conservation measures

The modelled total real water savings as a result of implementing water conservation measures on a greatly expanded irrigation area is substantial; a potential saving of ~2 BCM (Fig. 4) could be achieved from the existing and planned irrigation area upstream of the JNHPP. This saving is out of a total of ~5.9 BCM withdrawn from the river above the reservoir, of which 3.4 BCM of irrigation water is applied to the field.

Reduction of evaporation under conventional flood irrigation is achieved against the lowest marginal costs with the first BCM costing below 0.07 USD m^{-3} (Fig. 3). Measures such as a switch to sprinkler irrigation, in combination with improvements in conveyance efficiency, can reduce consumptive use and net irrigation demand but against increasingly higher marginal cost. For water savings over 1.5 BCM, costs rise rapidly, from more than 0.14 USD m^{-3} to over 0.5 USD m^{-3} for the last cubic metres, a cost close to that of modern desalination methods.

3.3. Value of water for irrigation use across the Rufiji River basin

Whether water conservation is worthwhile, from a financial point of view, depends on the value that alternative uses of water would generate. Fig. 5 shows the residual marginal value of the four irrigated crops, for areas where the crop is currently gown either rainfed or irrigated according to the land use dataset. Rice, maize and cassava are grown throughout the basin while sugarcane is concentrated in pockets in the upstream Great Ruaha Ruaha River catchment and further downstream where the Kilombero Sugar Company is situated, between various protected areas.

Residual values for irrigation water tend to be below 0.05 USD m^{-3}, with the exception of cassava – which represents a cluster of 'other'

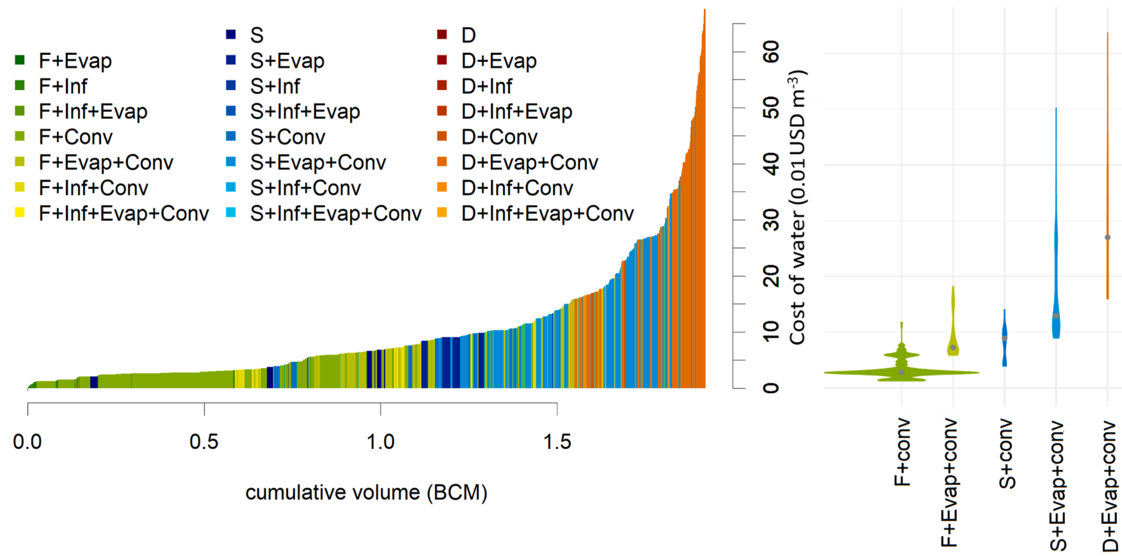

Fig. 4. Water savings cost curve (in billion m3 – BCM – along the x-axis), through implementation of various water conservation measures on current and planned irrigated area upstream of the JNHPP, organised by method of application with lighter colours indicating increasingly costly combinations of measures. In the violin plot on the right side the top five measures plotted, showing the distribution the median marginal cost (grey dot). F stands for surface irrigation (furrow or flood irrigation), S for sprinkler and D for drip, Evap is evaporation reducing measures like mulching while Inf stands for Infiltration enhancing measures and Conv comprises measures to reduce losses in the conveyance system. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

irrigated crops that can achieve high yields when irrigated. Residual values are low when overall gross profit of the crop is low, when additional irrigation adds relatively little extra yield, or both these conditions apply. Table 2 shows that maize, even with irrigated yields, is on average only just above break-even levels of productivity. Less optimal growing conditions in e.g. the Southern Highlands in the central part of the basin, tip the balance towards negative gross margin and, thus, negative residual value of irrigation water. Analysis by the Uyole Agricultural Research Institute in Mbeya indicates that farmers here are not likely to make a profit growing maize under the current cultivation and market conditions (Wilson and Lewis, 2015b). The capital to develop irrigation infrastructure and the institutions to fund ongoing operations and maintenance often do not warrant the production of staple crops (Mwamakamba et al., 2017; Stirzaker et al., 2014).

The range of calculated values for irrigation water is similar to that reported for case studies in other basins in the world (Bierkens et al., 2019; Hellegers and Davidson, 2010; Hellegers et al., 2013; Qureshi et al., 2018; Siderius et al., 2021a).

Our marginal value of water for ecosystem services is based on the projected 300 million USD tourism revenue gains per year through the preservation of the downstream Rufiji delta ecosystem and the NPP that relies on it. Increasing water savings by 0.5 BCM increments and routing these into the JNHPP reservoir, we analysed the threshold above which both biennial peak flow releases and firm energy production could be maintained. According to our model simulations using historical rainfall for the period 1981–2010, this would require water conservation in the order of magnitude of at least 1.5 BCM (Fig. 6) upstream of the reservoir. As a result of these savings, biennial peak releases of more than 2500 $m^3 s^{-1}$ would remain possible, even during a sequence of drought and low release conditions as in the 2000s, without compromising the ability of the reservoir to maintain firm energy output, which translates into a value of 0.20 USD m^{-3}.

Considerable risk remains, however, for example, in 2001 the peak release condition of the reservoir (two thirds full) is only just reached, and with assumed continued releases, would lead to a pronounced fall in lake levels, furthermore in 2006, the reservoir live storage is almost fully depleted. An additional 0.5 BCM of water savings (taking the total to 2 BCM) would add extra buffer in dry years (Fig. 6). During normal to wet years, with the reservoir near capacity, a peak environmental flow release leads to merely a temporary dip in lake volume with reservoir volume often able to recover by the end of the wet season.

An increase of 1.5 BCM in water savings leads to increased hydropower yield, not only because of the extra volume of water available, but potentially also because the reservoir can be operated at a higher level, especially in dry years, when energy can be generated more efficiently. During the extreme dry period in 2006, the efficiency reduction was kept at 17% (rather than 22%) due to reservoir storage not falling below 1.4 BCM. At higher reservoir levels, at which the reservoir is ideally operated, this difference is relatively minor, due to the non-linear level-storage relationship. Moreover, in our application, assuming peak releases to maintain environmental flows, this extra value is completely offset by increased reservoir outflows above the maximum turbine capacity of 2061 m s^{-1} during peak flow releases or spillage to avoid overtopping. As a result, around 10% of the extra inflow would not contribute to increased energy production at all. This level of energy generation results in an average marginal hydropower value just below 0.04 USD m^{-3}, using the kWh value of 0.137 USD (Section 2.4).

Fig. 7 compares marginal costs against the three sectoral values, as described above (values of water for agriculture (irrigation) are based on the residual values in Fig. 5). Generally, value is lower than costs of water conservation, due to low crop yields and low profitability of current agriculture. Costs of a third of measures do overlap with the hydropower values suggesting that a significant part of successfully implemented water conservation practices would be cost-effective in terms of increased energy. Nearly all the measures, apart from the most expensive ones (e.g., mainly those involving drip irrigation in combination with one of the other measures), would be worth exploring to achieve sufficient environmental flow peak releases to maintain the delta lake ecosystem and the tourism potential of the region.

4. Discussion

Using modelling and limited observational and secondary data we explored the potential water savings and costs of 24 combinations of water conservation measures and compared these with the value such water savings could generate from water use in three important

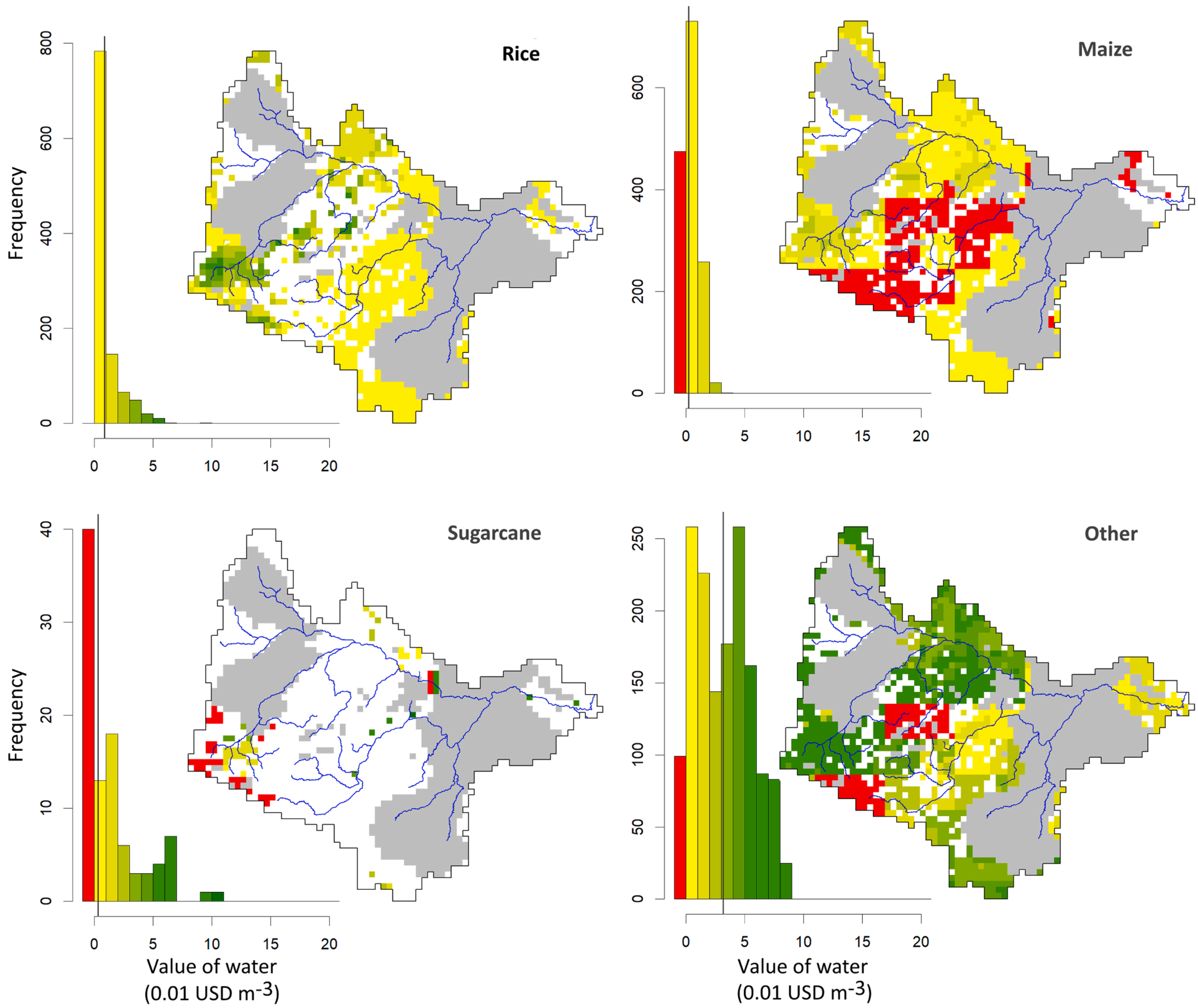

Fig. 5. Residual value of irrigation water based on model simulations of crop production (average over 1981–2010) and empirical cost and price estimates for four main irrigated crops in the Rufiji basin. In grey, National Parks and World Heritage Sites (source: UNEP-WCMC, 2014), in blue the Rufiji and its tributaries. Cropping intensity varies per cell. Cells where the crop is absent are in white. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

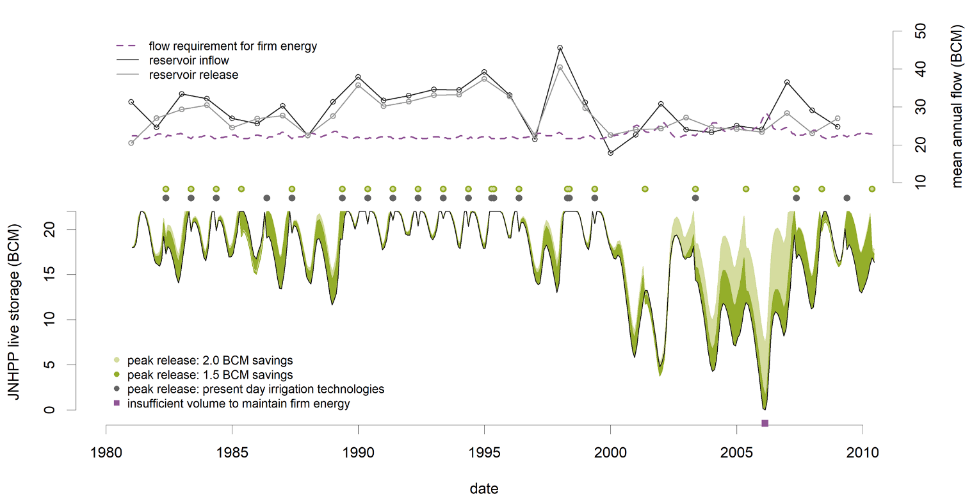

Fig. 6. Impact of water conservation on simulated JNHPP reservoir volume and environmental flow peak releases. Modelled historical Rufiji flow series from Siderius et al. (2018). Green and black dots indicate months with an average release of 2500 m3/s or more, which is required once every two years at a minimum to flood and sustain downstream lake ecosystems. The green colour shading indicates the difference in JNHPP storage level as a result of two levels of upstream water savings in agriculture; 1.5 and 2.0 BCM per year. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

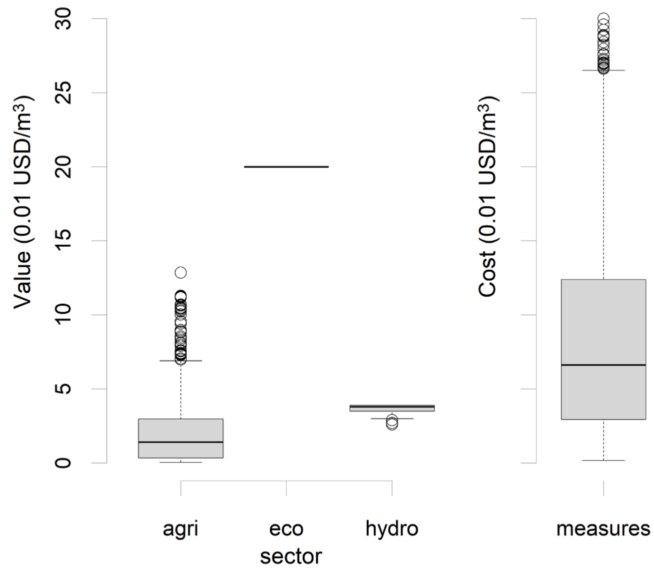

Fig. 7. Value of water for different sectors (irrigated agriculture, ecosystem services (whole Rufiji River basin tourism value), hydropower) vs modelled volumetric cost of water conservation measures in agriculture (Cost of measures is truncated above 0.3 USD m^{-3} for plotting reasons).

economic sectors; agriculture, energy and downstream ecosystems which have a high tourism potential. The cost of water conservation measures was found to be higher than the value of most uses of water for growing crops and the median value for hydropower generation and lower than the ecosystem value. Nevertheless, under high-end irrigation expansion plans, our modelling assumptions and existing rainfall and river flow conditions (1981–2010), upstream water savings of at least 1.5 BCM, if implemented effectively, would make financial sense by reducing potential trade-offs between use of water for hydropower and ecosystem services (allowing peak environmental flow releases even in dry years, without reducing firm energy generation).

Due to limited data availability we have taken a simple approach to estimating water-related ecosystem value by focusing only on aggregate wildlife tourism, an important contributor to Tanzania's GDP, for which an estimated value exists (World Bank Group, 2015). Environmental flows through the Rufiji delta support numerous other functions such as Tanzania's commercial shrimp fisheries, existing flood recession irrigation, mangroves that provide coastal erosion protection and whale shark habitat around Mafia Island National Park (Hamerlynck et al., 2011). Conversely, we have not included additional costs to make the Southern Circuit more attractive for tourism, such as better connectivity (World Bank Group, 2015), although this would be tied to other benefits such as providing market access for agriculture and lowering prevailing high input costs. Our estimates of water use values should therefore be considered indicative.

We did not analyse conditions in which energy generation at the JNHPP would be optimised above the firm energy level. Our simulations suggest there is only limited scope to increase average outflow beyond the approximately 700 $m^3 s^{-1}$ required to maintain firm energy, without increasing the risk of failure to meet environmental flows constraints. However, this could be explored with tools evaluating more advanced operational rules, able to handle different combinations of multi-sector objectives.

We based our value of hydropower energy (~ 0.04 USD m^{-3}) on a kWh cost price of 0.137 USD from Tanzania's Power System Master Plan (2016). While this value is lower than earlier estimates of 0.06 USD m^{-3} for hydropower at the upstream Mtera reservoir (Kadigi et al., 2008) or a commonly used value in hydro-economic optimisation of 0.08 USD m^{-3} (Siderius et al., 2016; Whittington et al., 2005), the kWh estimate is higher than that used by Hartmann (2019), the current average retail price of electricity (World Bank Group, 2018) or the levelised cost of alternative energy options such as gas and solar, or hydropower plants in neighbouring countries such as Inga3 in Congo (Deshmukh et al., 2018). As such, our value is likely a high-end estimate of the financial benefit of hydropower.

We exclude the demand of potential new irrigation schemes in the Rufiji delta, downstream of the JNHPP. We expect that this demand could be accommodated by the firm energy release volumes from the JNHPP. Whether large scale irrigation should be developed here at all remains questionable. Peak releases to flood the delta lake ecosystem will put considerable demands on intake design raising costs. According to Hamerlynck et al. (2011), earlier exploration of the irrigation potential in the Rufiji delta found that, in general, there is enough rain for two crops a year and that therefore irrigation is not a necessity and can only be successful, as a supplement in bad years, if the water can be provided at a relatively small cost. More generally, large-scale irrigation plans in many parts of Africa are over-optimistic with expansion far slower than planned and much smaller when finally established (Higginbottom et al., 2021; Mwamakamba et al., 2017). It is therefore highly likely that these estimates, taken from official documents, are at the upper limit of what is actually going to be achieved.

Our results are based primarily on a modelling system that accounts for water budgets on a ~8 km by 8 km grid resolution (the hydrological model is validated on observed flows, but still makes assumptions about wetland systems and ungauged parts of the basin (Siderius et al., 2021a)) and produces reasonable simulation of crop yields. However, we note that there are very limited recent observations of actual abstractions, applications and return flows for the irrigated areas in the basin and therefore these results should be considered indicative. There is no substitute for in situ data on water use and performance of water conservation measures. We rely on idealised, though restricted, conditions in the model without any validation based on observations of the effectiveness and sustainability of the range of water conservation measures in a local context. While we correct for the effect on return flows in order to avoid overly optimistic rates of savings, these more efficient ways of irrigation application will result in a temporal and spatial redistribution of return flows in existing irrigation systems, with more water remaining in the river main stem and tributaries at the expense of delayed flows through the irrigation drainage system (whether natural or constructed), affecting those who currently abstract return flows closest to the point of initial application (Lankford, 2004). And while our production cost estimates and prices are derived from local basin studies, combined with national statistics, we acknowledge that averages do not address the often uneven distribution of benefits and costs of water conservation measures between various types of farmers (Venot et al., 2017).

There are additional social costs with higher efficiency systems such as managing the shared responsibilities on collectively owned technically complex equipment and their operation and management costs. New technology also needs to align with local decision-making structures and technical know-how, however, new systems bring employment opportunities so that some costs may be offset by considering the broader community benefits. The impact on groundwater which has largely unexplored potential (Cuthbert et al., 2019), and on those who rely on this source of water, would also need further scrutiny.

Our basin-scale analysis overlooks sub-basin scale trade-offs that arise at various points across the basin particularly associated with increasing water use for agriculture and environmental flow requirements at key locations with high ecological or tourism value. For example, long-running tensions exist in the Great Ruaha catchment between smallholder agriculture and pastoralists, irrigation expansion, land-grabbing and conservation (Kashaigili et al., 2005; Lankford, 2004; Walsh, 2012). Similar issues relating to access and how political power (formal and informal) is distributed and exercised affect the way in which different actors access and utilise efficiency gains (e.g. Lankford, 2013). Domestic demand, not included in our analysis, tends to have a higher value than agriculture, hydropower or wildlife tourism. Demand in terms of volume is comparatively small, though, and trade-offs with other sector demand seem minor. Indirectly, however, deforestation linked to agricultural expansion could impact water quality affecting suitability for drinking water (Ashagre et al., 2018). Cost savings of 4.6–17.6 million USD per year for forest conservation under water treatment work conditions were estimated by Ashagre et al. (2018). Our water conservation measures, especially those targeting evapotranspiration reduction and soil infiltration, might not fully prevent but could minimise the impact of land conversion.

We evaluated the possibility of maintaining firm energy and environmental flows for a near-present 30 year time period but more severe multi-annual droughts have occurred earlier in the 20th century and climate change projections suggest a further increase in variability (Siderius et al., 2021b). Average flow is currently ~ 30BCM, but can be as low as 20BCM in dry years. Increased variability in rainfall and runoff in combination with ambitious formal irrigation expansion plans alongside expansion through farmer-led processes is likely to test the buffering capacity of even the JNHPP reservoir. Contingency planning for such events needs to be in place with particular attention to the vulnerability, and the high added value, of the delta ecosystem. Such planning requires basin-wide institutional strengthening that recognises sector interdependencies, the multiplicity of water users and how they are impacted by restrictions (Venot et al., 2021), capacity to implement and maintain infrastructure development programmes, coupled with a need to focus on factors affecting performance of local water user associations, while taking into account the needs of the poorest (Richards, 2019; Sokile et al., 2003).

5. Conclusions

Given completion of the JNHPP and ambitious irrigation expansion plans considerable water savings would be financially viable in the Rufiji River basin but only using water conservation measures lying at the lower end of the marginal cost curve (upgrades to the conveyance system, followed by evaporation reduction and application by sprinkler). Controlling for the impact on return flows reduces the amount of water each individual measure saves, and increases its volumetric cost. At a median cost of 0.07 USD m^{-3}, water conservation is too expensive for the majority of agricultural applications, higher than hydropower value but well within the estimated ecosystem value. If the ambitious formal irrigation expansion plans are realised, without water conservation measures, trade-offs between energy production and downstream environmental flow demands will be harder to negotiate, with considerable risk of jeopardising the highest financial value – that of the ecosystem – in times of drought. Noting that our financial estimates are illustrative and not total economic value, taken together, the major ongoing and planned development of hydropower and irrigation in the Rufiji River basin will increase basin-scale trade-offs in the water, energy, food and environment sectors. This analysis demonstrates several steps towards understanding the value of water in its different uses and thus makes a methodological contribution towards assessing and implementing integrated sector decision-making along the lines of the water-energy-food-environment nexus agenda. The method is applicable to other regions and illustrates how a combination of financial considerations alongside biophysical assessment explains why not all water saving measures will be financially feasible. Such information could, alongside strengthened multi-sector and multi-stakeholder engagement processes, contribute to informed debate on water management and allocation, helping to identify a basis for making 'agreeable' trade-offs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2022.107548.

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