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Review

Conserving Rivers and Their Biodiversity in Tanzania

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Abstract: The United Republic of Tanzania (Tanzania) is rich in freshwater resources and biodiversity. In this article, we highlight the importance of Tanzanian rivers and make a case for the conservation of the freshwater and terrestrial species that rely on these rivers. We provide an overview of current knowledge on Tanzanian rivers and discuss progress towards implementation of the National Water Policy (2002) and Water Management Act (2009), two legislative instruments that have motivated environmental flow assessments on at least six major rivers and offer legal backing for river conservation. We examine major challenges that pose significant threats to water security for river ecosystems and humans in Tanzania, among those: (1) human population growth, (2) agricultural expansion, (3) river flow alterations, (4) industrialization, (5) introduced species, and (6) climate change. We conclude by offering recommendations for future river conservation efforts in Tanzania.

Keywords: East Africa; freshwater; policy; tropical; environmental flows

1. Introduction

The United Republic of Tanzania—an East African nation renowned for iconic landscapes like Serengeti National Park, the Eastern Arc Mountains biodiversity hotspot, and Mount Kilimanjaro—is remarkably rich in freshwater resources. Tanzania is the only country to hold territory in all three of the African Great Lakes and is crisscrossed by numerous large river systems, such as the Rufiji, Mara, Malagarasi, Pangani, Ruvuma, Wami and Ruvu. Although the lakes are recognized as global centres of species radiation in Cichlid fishes, the country's rivers—less well-known internationally—sustain much of Tanzania's freshwater and terrestrial biodiversity and provide water to support a growing human population that is increasingly concentrated in urban areas.

Tanzania also possesses some of the most pro-environmental legal and institutional frameworks for water resources management in the world. For decades, water resources in Tanzania largely have been managed according to river basin boundaries [1]. In the early 2000s, Tanzania revamped its legal frameworks for freshwater governance under a new National Policy for Water [2] and a subsequent Water Resources Management Act [3]. These legal instruments explicitly recognized river and riparian ecosystems as users of water, and their implementation has led to a wave of studies in rivers across the country to estimate ecosystem flow needs [4]. Consequently, Tanzania has been one of the most active adopters of the first Brisbane Declaration and Global Action Agenda for Environmental Flows issued in 2007 that called for '*estimating environmental flow needs everywhere immediately*' [1,5].

Nevertheless, scientific study of Tanzanian rivers, as well as widespread recognition of their conservation importance, remains highly limited. Comparatively, the African Great Lakes and Tanzania's terrestrial ecosystems and their fauna have been the focus of many more studies than rivers. For example, between 1977–2017, 758 articles were published about the Serengeti-Mara region of Tanzania and southern Kenya in indexed journals; only 54 of those were related to rivers, most (43/54) published in the past decade (E. Anderson, unpublished data). Current demographic and environmental trends suggest that satisfying water needs of Tanzania's human population without compromising the integrity of its river ecosystems will be increasingly challenging, even in the presence of pro-environmental legal and institutional frameworks for water resources management. Tanzania has one of the Earth's fastest growing human populations and is poised for major agricultural expansion, new dams, and increased urbanisation in the near future. Climate change predictions for East Africa and introduced species add a further level of complexity to river management and freshwater biodiversity conservation.

Given this context, we see a need to herald the importance of Tanzanian rivers and strengthen arguments for the conservation of the freshwater and terrestrial species for whom rivers are critical. In this article, we offer the first general overview of the river systems of Tanzania from a biodiversity conservation standpoint. We provide a summary of Tanzanian river geography and present current knowledge on riverine biodiversity, as well as highlight terrestrial species' links to rivers. Additionally, we describe how recent efforts to implement legal frameworks for water resources management have helped elevate scientific study of Tanzanian rivers. Finally, we discuss major challenges and opportunities for river conservation in Tanzania and conclude with a set of recommendations for future efforts.

2. Tanzanian Rivers and Their Biodiversity: An Overview

Our focus in this article is mainland Tanzania (885,800 km^2), located along the Indian Ocean coastline, neighboured by Kenya to the north and Mozambique to the south. Mainland Tanzania's western and southern borders cross through the African Great Lakes—Victoria, Tanganyika, and Nyasa. Several major river systems drain mainland Tanzania (Figure 1). The Pangani, Wami, Ruvu, Rufiji, and Ruvuma rivers flow eastward, descending from Eastern Arc Mountain blocks, winding through coastal forests, and eventually draining into the Indian Ocean. Much of the country's human population, including urban centres like Dar es Salaam (6 million people) and Dodoma (2 million people), and major agricultural regions are located in these basins. Several other rivers such as the Malagarasi, Kagera, Ruhuhu and Mara flow towards the Tanzania Lake basins of Tanganyika, Victoria and Nyasa.

Most of Tanzania experiences a marked difference in precipitation between wet and dry seasons; river flows reflect this seasonality. Some rivers experience a bi-modal hydrograph, with peaks in flow that correspond to the long (*masika*) and short (*vuli*) rains; other rivers exhibit a uni-modal hydrograph [6,7]. Rivers are key ecosystem elements of several of Tanzania's protected areas and critical to wildlife survival, particularly during dry seasons when other sources of water may dry out. For example, in the Serengeti National Park, the Mara River provides one of the only perennial sources of water for large wildlife and acts as a guidepost for wildebeests that cross the river multiple times during their annual migration (Figure 2a). Saadani National Park, located at the confluence of the Wami River with the Indian Ocean, protects the Wami's estuary region, which also supports one of the most productive prawn fisheries along the East African coastline; intensive periods of prawn fishing coincide with high flows in the Wami River (Figure 2b) [8].

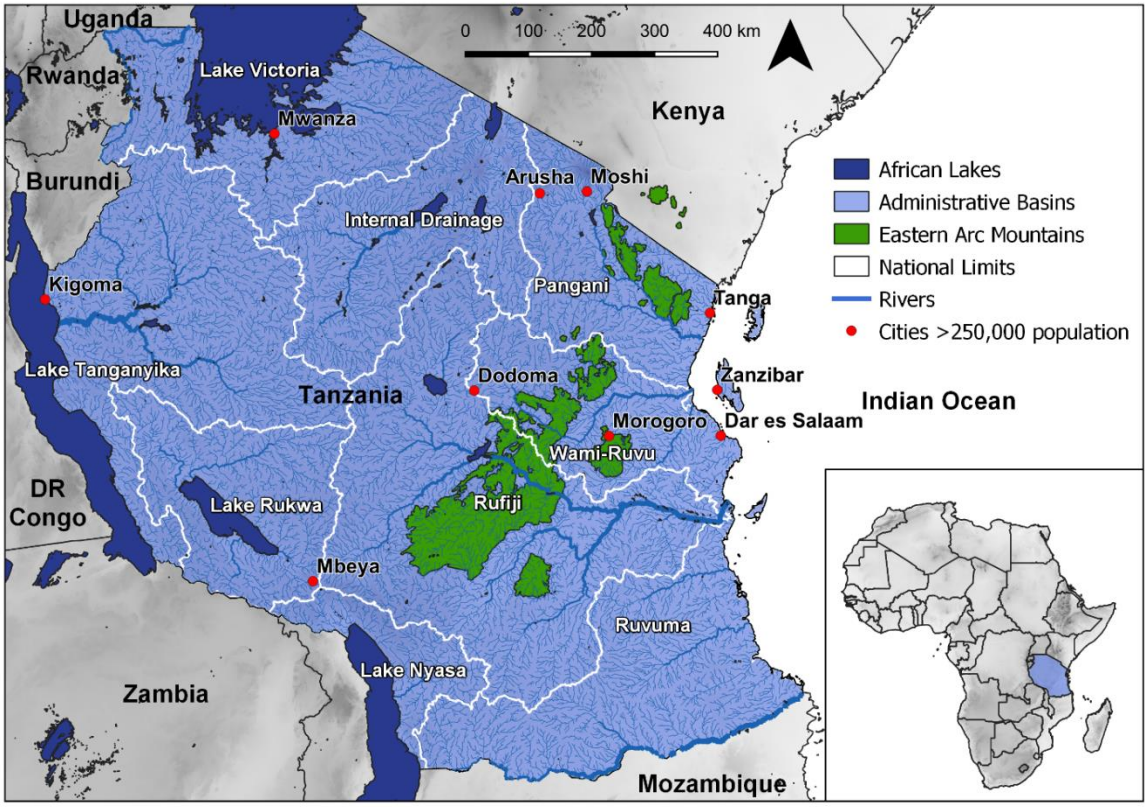

Figure 1. Tanzania is divided into nine administrative basins under the Tanzanian Ministry of Water, which generally follow natural river or lake basin boundaries. The country's largest river systems are the Rufiji, which drains to the Indian Ocean, and the Malagarasi, draining westward to Lake Tanganyika.

(**a**) (**b**)

Figure 2. (**a**) Wildebeest cross the Mara River multiple times during their annual migrations in the Serengeti-Mara region of northern Tanzania and southern Kenya. This event draws thousands of tourists annually. Photo: D.M. Post. (**b**) The lower Wami River and its estuary are important parts of Saadani National Park and considered nursery areas for prawns. Photo: E.P. Anderson.

Tanzanian rivers originating in Eastern Arc Mountain blocks fall into a newly recognized category of Tropical Montane Rivers, as defined by Encalada et al. [9]. Eastern Arc rivers exhibit characteristics of Tropical Montane Rivers such as: Predictable change in water temperature with elevation; frequent disturbance events like landslides or extreme hydrologic events; habitat heterogeneity; and connectivity with headwater and lowland areas. Downstream, the deltas of many Eastern

Arc-origin rivers—notably the Rufiji and Ruvuma—are recognised as areas of ecological and social importance in the Western Indian Ocean. These rivers export high loads of sediments from Eastern Arc Mountain blocks, which form and maintain floodplain areas in lower gradient parts of their basins near the Indian Ocean coastline, in combination with tidal influences [10]. Connecting the mainland to the coast, riverine floodplains, and deltas contain nursery areas for aquatic biota, act as sinks for carbon, offer defence against storms, and provide innumerable ecosystem services to human populations [10,11].

The current state of knowledge of riverine biodiversity in Tanzania is limited. For example, Eccles' *Field Guide to the Freshwater Fishes of Tanzania*, the primary reference on this faunal group, was published more than 25 years ago [12]. Species records for most river basins in Eccles [12] were based on fisheries information and very limited collections and therefore likely underestimate fish species richness, particularly for endemic, rare, and non-fisheries species. Even today, most rivers in Tanzania still have not been extensively sampled for fishes or other aquatic biota; a similar situation is observed across other East African countries as well [13].

Given this scenario, several recent initiatives have aimed to elevate scientific knowledge of freshwater fishes and macroinvertebrates inhabiting flowing water environments in Tanzania. An estimated 1257 freshwater fish species have been documented in freshwaters of continental Tanzania, of which at least 773 are found in the lakes Victoria, Tanganyika and Nyasa [14]. For freshwater mollusks, an estimated 159 species have been documented, 76.5% of which are gastropods and 23.5% bivalves (L. Kaaya, unpublished data). Tropical montane rivers draining Eastern Arc mountain blocks are likely to harbour a highly endemic freshwater fauna, given that this region is renowned for high species richness and endemism across multiple taxonomic groups—plants, birds, mammals and amphibians, in particular [9,14–17]. For example, at least three endemic Odonata (dragonflies and damselflies) are known to spend their reproductive stages exclusively in Eastern Arc montane rivers [18], and in 2007, an ichthyofaunal survey of Eastern Arc rivers reported 75 fish species, including 11 newly described [19]. Similarly, a rapid assessment of the aquatic biota of the Wami and Ruvu Basins completed in 2013–2014 added new species records of fishes and amphibians for those basins [20]. Finally, recent studies in classifying river ecosystems, coupled with the development of bio-assessments for macro-invertebrates in Rufiji, Wami-Ruvu and Pangani, have increased awareness of freshwater biota, and the high level of discovery that remains [21–23].

Environmental flow assessment studies (see Table 1 and subsection below) have included snapshot sampling for fishes and macro-invertebrates, providing additional data and in some cases the first field sampling campaigns for Tanzanian rivers [24–29]. For example, an initial environmental flow assessment in the Wami River basin identified five different sites where field sampling was conducted during both dry and wet seasons in 2007, including sampling of riparian biota, macroinvertebrates and fishes. Of the 37 species of fish that were previously reported from the Wami River basin [12], 28 were collected during these sampling events [4]. Similarly, an environmental flow assessment conducted in the Rufiji River basin documented 27 species of fish from five sampling sites, about half of the species known from the region. This effort also gathered evidence on the ecology of several fishes, including data on longitudinal migrations of several species (e.g., *Labeo* spp., *Hydrocynus vittatus, Anguilla* spp., *Alestes* sp., *Barbus macrolepis* and *Mormyrus* sp.) and lateral migrations between the river and floodplains for other species (e.g., *Clarias* sp. *Brycinus affinis*, and *Schlbe moebusii*) [27]. This kind of information is critical to understanding the ecological linkages to river flows, as many of these migrations are linked to flow pulses or flooding events.

Table 1. Summary of selected environmental flow assessments (EFA) realized for Tanzanian rivers since the passage of the National Water Policy in 2002.

River System	Timeline for EFA	Approach/Methodology	Key Riverine and Riparian Features; Protected Areas	Challenges for River Conservation and Management	References
Pangani	2003–2005	Used modified downstream response to imposed flow transformation (DRIFT) approach to develop scenarios	Eastern Arc montane streams and forests; Mt. Kilimanjaro National Park	Competition for land; agricultural expansion; urban and rural water interests	[4,30]
Great Ruaha (tributary of Rufiji River)	2003–2005	Initial EFA with semi-holistic approach; used desktop reserve model and flow duration curve analysis based on the hydrologic data, with some information on the ecology of Ruaha National Park	Ruaha National Park; Usangu Plans and wetlands, designated as an important bird area by BirdLife International	Expansion of agriculture and livestock grazing on the Usangu Plains; cease of dry season flows in the Great Ruaha River and drying out of wetland areas	[4,31–33]
	2007	Full EFA using building block methodology			[34]
Mara (tributary of Lake Victoria)	2005–2012	Modified building block methodology; field campaigns were conducted over several years and two sets of flow recommendations were developed, the first focused on the Kenyan side and the second including Kenya and Tanzania	Serengeti National Park and Mara wetlands complex; Mara River is one of only perennial rivers in the region	Transboundary nature of the basin (65% in Kenya; 35% in Tanzania)	[4,24,31,35]
	2018–present	Focus on Tanzanian side of the Mara River, using PROBFLO			[36]
Wami	2007, 2012–2013	Initial EFA using a modified building block methodology; flow recommendations later revisited after additional fieldwork	Eastern Arc montane rivers; Wami estuary; Saadani National Park	Expansion of irrigated agriculture; domestic water supply withdrawals; freshwater inflows to the Wami estuary and surrounding Saadani National Park	[4,26]
	2014–2015	Study of freshwater inflow requirements for the Wami River estuary and Saadani National Park			[37]
Ruvu	2012–2014	Initial EFA using modified building block methodology	Eastern Arc montane rivers; estuary and coastal rivers; water supply for Dar es Salaam	Increasing human population growth and industrialisation in Dar es Salaam, and related demands for water	[25]
Rufiji	2014–2016	Application of a desktop reserve model and a modified building block methodology; additional consideration given to social-ecological significance of river flows	Wetlands, river floodplains and coastal zones	Growth of irrigated agriculture, particularly in the Kilombero River Valley	[27]

Knowledge limitations on Tanzanian rivers are not limited to obligate freshwater biota. Numerous other species in Tanzania are semi-aquatic or have life histories dependent on freshwater systems, and the flow-ecology linkages that are critical to these species' survival is a growing area of research. For example, hippopotami (*Hippopotamus amphibius;* hippos hereafter), native to many areas of Tanzania, need to submerge themselves in water during the daytime to aid in thermoregulation and to avoid skin damage from solar radiation. Recent studies of hippos in Tanzania's Great Ruaha River suggest that alterations of aquatic habitats, in particular surface water withdrawals, are the largest threat to hippo distribution and abundance, and the species' overall viability [38]. Other studies by Stears et al. [39] in the Ruaha River system have suggested that hippos typically stay <800 m from riverbanks, and that the importance of river flow to hippo ecology and population dynamics varies by life stage. Additionally, the perennial Tarangire River, sustained by its associated wetland and swamp ecosystems, provides crucial dry season refuge for larger numbers of mammals including a high density of elephants and other plains game animals such as the African buffaloes (*Synceros caffer*), zebra (*Equus burchellii*) and the wildebeest (*Connochaetes* sp). Understanding of the freshwater needs of these organisms is increasing, but still limited.

Finally, a relatively new line of research has started to examine the interactive effects of large animal resource subsidies and hydrology on river ecosystem ecology. Studies along the Mara River of Kenya and northern Tanzania have documented the strong role that hippos play in river nutrient and oxygen dynamics, as one individual hippo may contribute an estimated six kg/day of waste [40]. Aggregations of hippos in pools can lead to an accumulation of organic matter, that when flushed by a pulse or peak hydrologic event, can cause a large drop in dissolved oxygen, often leading to fish kills [41]. The annual wildebeest migration is an additional source of animal resource subsidies to the Mara River and also somewhat hydrologically mediated [42]. Wildebeests cross the Mara River multiple times during the migration and many do not survive, resulting in animal carcasses in the channel. When these crossings occur during low flows, there is chance for increased predation by crocodiles on wildebeests, but when the crossings occur during high flows, the likelihood of drowning is increased.

3. Frameworks for River Conservation and Management

The NAWAPO (2002) and WRM Act (2009) offer a hierarchical approach to river management, with the Tanzanian Ministry of Water operating at a national scale, nine Basin Water Boards with jurisdiction at river or lake basins, and Catchment Committees at sub-basin levels. Beyond these levels, Water Users Associations (WUAs) provide a formal means for public participation in water management at a smaller geographic scale [43]. WUAs are designed to be the lowest level in the hierarchical water management structure in Tanzania, covering all or parts of the watersheds and delegating responsibility for water conservation and some aspects of water allocation permitting to residents of the respective watershed area [44]. For water allocation decisions involving Tanzanian rivers, the NAWAPO and WRM Act established an order of priority by which needs of different user groups must be considered and satisfied. Domestic needs for water—such as water for drinking, bathing, cooking or subsistence—receive first priority. Water to sustain ecosystems, now and into the future, is accorded second priority, followed by water needs of agriculture, hydropower, industry and other off channel users [2,3].

Giving second priority to ecosystems in water allocation decisions requires that Tanzania estimate the environmental water needs—also known as environmental flows—for all major rivers. According to the internationally-accepted, revised Brisbane Declaration [5], the term environmental flow refers to: *the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being* [45]. In this century, Tanzania is among a growing list of countries that have increased geographic coverage of environmental flow assessments, and in-country capacity to complete them [46,47]. To date, environmental flow assessments have been realized for at least six Tanzanian rivers, including the Pangani, Wami, Ruaha,

Mara, Ruvu and Rufiji (Table 1) [4,24–27,31]. These assessments have been undertaken by the Ministry of Water with national and international support and have used a variety of methods, but most would fall within the category of 'holistic' approaches to environmental flow assessment [1]. For example, an environmental flow assessment for the Pangani River Basin (2003–2005) employed a scenarios approach, following a modified downstream response to imposed flow transformation (DRIFT) methodology developed in South Africa [30]. An initial environmental flow assessment was conducted in the Wami River Basin in 2007, co-led by the Wami River Basin Water Board with facilitation from U.S.-based scientists, used an adapted building block methodology BBM [48]; it involved at least five scientists from the University of Dar es Salaam that conducted literature reviews and fieldwork in their respective disciplines—hydrology, hydraulic engineering, riparian ecology, aquatic ecology, and fluvial geomorphology.

Over time, environmental flow assessments and the capacity to conduct them have grown considerably in Tanzania [1]. Within just a decade of implementation of the WRM Act (2009), more than half of Tanzania's major river basins now have at least one completed assessment; many have repeated studies [24,25,31]. A growing group of Tanzanian scientists and Ministry of Water officials have participated in these efforts, including at least five scientists who have been part of three or more assessments. Consequently, these efforts have resulted in flow-ecology linkages being incorporated into the research programs of Tanzanian scientists, journal articles on environmental flows, and increasing interest in the topic in East Africa. Compared with most other African countries—with the exception of South Africa, an early pioneer—Tanzania is now an international leader in the science and practice of environmental flows [1,4,47].

Beyond mandates for assessment and implementation environmental flows, the URT [2] and WRM Act [3] also contain mandates for public participation in water resources management in Tanzania. The primary legal mechanism designed to facilitate this participation is the formation of WUAs. As part of the implementation of new legal frameworks for water, the Tanzanian Ministry of Water has hired dozens of social scientists for its national office and for the Basin Water Boards to facilitate the process of formation of WUAs across the country. As of 2017, 102 WUAs had been formed in Tanzania following the passage of the NAWAPO and WRM Act [43]. Similar to environmental flow assessments, the process of formation of Water User Associations (WUAs) took varied routes, often with international donor or non-governmental organisation assistance [44]. WUAs are intended to provide support to Basin Water Boards and may assist with tasks like collection of water fees, conflict management, and water monitoring. However, in our observations and from the summary of Tanzania's experiences with WUAs provided by Kabogo et al. [43], to date there appears to have been little participation of WUAs in the assessment and implementation of environmental flows.

4. Challenges for the Future Condition of Rivers and Their Biodiversity

Despite strong legal instruments for freshwater conservation, future changes in freshwater supply and demand in Tanzania will present challenges for balancing future river water allocations between ecosystems and human users. For example, Miraji et al. [49] suggests that river flows in the Wami-Ruvu Basin are declining in part because of high rates of water withdrawals, which threatens numerous species of amphibians and reptiles. Current projections suggest that human demand for freshwater will substantially increase in the next decades. Human population growth, agricultural expansion, planned construction of new dams, industrialisation, introduced species, and climate change are all issues relevant on a national scale; however, these challenges are likely to be most acute for river systems that support agricultural and urban areas in eastern Tanzania. We provide an overview of these trends below.

4.1. Human Population Growth in Urban Areas

As of the last census in 2012, the population of Tanzania stood at 44.9M people [50]. This number is approximately double the 22.5M recorded in 1988, and six times the 7.5M in 1948 [51].

Rapid population increases were precipitated by a few general factors, among them improvements in health care and disease control, declining death rates from medical advances, and increased birth rates [52,53]. Additionally, infant mortality has decreased by about two-thirds over the period 1978 to 2012, with 137 deaths per 1000 live births in 1978 to 46 deaths per 1000 live births in 2012 [50]. The total population of Tanzania is projected to reach 62.3M people by 2020 and 82.9M people by 2030 [53]. These trends suggest that within the next 15 years the total population of Tanzania will approximately double, placing it within the nine countries responsible for half of world population growth from 2015–2050 [53].

Trends in urban areas illustrate the tension between human population growth and conservation of riverine freshwater resources. The cities of Dar es Salaam and Dodoma—Tanzania's largest urban centre and administrative capital, respectively—source much of their water from the Ruvu River [54]. Within this context lies the uncertainty of water security for future human populations in Tanzania. Global guidelines suggest that each person requires a minimum of 1000 m^3 of water per year to satisfy basic human needs; declines below this threshold constitute water scarcity [55]. Water stress occurs when access to water resources falls below 1700 m^3/person/year [56]. On its own, the population growth of Dar es Salaam will increase pressure on drinking water resources within the country, as the city achieves "megacity" status before 2030, or a population that exceeds 10M people. Currently, Dar es Salaam is the world's second fastest growing city, and the population is expected to more than double from its current population of 6M people to 13.4M people by 2035 [57].

4.2. Agricultural Expansion

The agriculture sector employs the majority of Tanzanians—approximately 70% of the labour force, accounting for 24% of GDP [58]. Tanzania has approximately 44 million ha of arable land, yet until recently only 24% was under cultivation [58,59]. Of this arable land, an estimated 29.4 M ha has the potential for irrigation, but just 1.5% of this land is irrigated, as 90% of the agricultural output is rain fed [58]. Considering Tanzania's potential for agricultural development, establishment of agricultural corridors through private-public partnerships has emerged as a viable solution to spur this development and potentially improve economic conditions for rural human populations.

Kilimo Kwanza (Agriculture First) is the agricultural component for achieving Vision 2025, which aims to transform Tanzania from a low to middle-income economy by 2025. Kilimo Kwanza is a public-private initiative seeking to improve the agriculture sector for economic growth and hence poverty reduction [58]. The accelerated agricultural expansion proposed by these private-public partnerships coupled with human population growth represents a challenge to the implementation of integrated water resources management (IWRM) in Tanzania. SAGCOT, or the Southern Agricultural Growth Corridor of Tanzania, is a major initiative of Kilimo Kwanza that aims to combine $2.1B in private investments and $1.3B in public investments over 20 years to triple the agricultural output in the designated area [60]. SAGCOT private partners include companies like Monsanto, Unilever and Yara, non- profit entities such as The Nature Conservancy and Wildlife Conservation Society, farmer organisations like the Agricultural Council of Tanzania and the Rice Council of Tanzania as well various offices within the Tanzanian government (SAGCOT Centre Ltd, n.d).

Spatially, SAGCOT accounts for one-third of the mainland Tanzania, stretching from the Lake Rukwa Basin through the Mbeya, Iringa, Ruvuma and Morogoro regions [61]. However, concerns exist on whether the SAGCOT initiative adequately considered socio-economic and environmental factors when strategically selecting regions suitable for agricultural intensification [62]. Most agricultural investments seek to maximize profits by minimizing investments though the conversion of land with high yield potential, while overlooking natural habitats and ecosystem services provisioned by these habitats [62]. Taylor [63] suggests that although SAGCOT projects must undergo an environmental impact statement, a review of investments within SAGCOT areas reveal that investors are relying heavily on government institutions to enforce environmental standards. In terms of water resources, SAGCOT-related agricultural expansion projects could heavily draw from surface water resources in

the Rufiji Basin, particularly the Kilombero and Lower Rufiji sub-basins. The Wami-Ruvu, Lake Rukwa and Lake Nyasa basins may also be affected by SAGCOT projects. If surface water shortages ensue, recent studies [49,64] contend that groundwater abstraction may be encouraged as alternative for smallholders to continue irrigating their crops. Furthermore, recent work in the Kilombero Valley within the Rufuji Basin found reduced water quality (higher levels of turbidity, nitrate and ammonium) in streams used for irrigation within downstream sampling sites when compared to upstream sites [65]. Although this finding is reflective of one study site in relation to the effects of irrigation on water quality, the growth of SAGCOT related irrigation schemes should be accompanied by research to determine the scaled implications of changes in water quality on ecosystem and human health.

4.3. River Alterations and Dams

Several dams for hydroelectricity or irrigation water diversion already exist in Tanzania. More new dams are planned, as is the case for many African countries [66]. Decades of research worldwide have shown that river alterations caused by the presence and operation of dams affect the ecological conditions of river, riparian, and floodplain areas and compromise the survival of species associated with these environments [67]. In turn, these ecological changes and species' declines typically decrease the quality and availability of river and floodplain ecosystem services, thereby affecting human populations. These kinds of linked social and ecological consequences are already being seen for existing dams in Tanzania.

The existing Kihansi Dam in Tanzania presents a well-known case of ecological change as a consequence of a hydroelectric dam. The project was closed on the Kihansi River in 2000 and diverted an estimated 85% of the river's flow. Studies have shown subsequent changes in water quality and community composition of wetland plants and amphibian species, most notably the endemic Kihansi Spray Toad (*Nectophrynoides asperginis*), whose only known habitat is the humid areas created by the spray of the original waterfall at the dam site [68,69]. Once the dam was closed and began operations, this spray habitat disappeared and an international captive breeding and reintroduction effort to save the toad from extinction was launched.

New hydroelectric development represents a potential source of future electricity for Tanzania, and a way to increase the percentage of the population connected to the national electricity grid, estimated at ~15%. Recognizing this potential, the Tanzanian government recently authorized the construction of a multi-billion-dollar hydroelectric dam expected to bring electricity to millions of people [70]. The dam will be located on the Rufiji River within the Selous Game Reserve, a popular tourist destination and a UNESCO World Heritage site [70]. Construction of the dam will require clearing 2.6 million trees to inundate 1200 sq km of land that includes habitat for black rhinoceroses, elephants, and other species, while threatening the livelihoods of tens of thousands of downstream users who depend on the naturally dynamic flooding regimes of the Rufiji for agriculture and fisheries [10,66,71].

4.4. Industrial Development

Tanzania's Vision 2025 aims to transform the country into a semi-industrialized state, for which the contribution of industries to the economy should reach a minimum of 40% of the GDP. In order to achieve the 8% per annum GDP growth rate articulated under Vision 2025 [72], the manufacturing sector must meet a 15% per annum target to achieve a gross manufacturing value of $16B USD by 2025 [73]. Rapid industrialisation without effective pollution control mechanisms could impose deleterious effects on environment. To date, the pollution of water resources has resulted in the degradation of river systems, as well as other natural resources such as land, soil, and vegetation. For example, a recent study lead by Water Witness International and Shahidi wa Maji in Tanzania revealed that industrial pollution in Mzimbazi River in Dar es Salaam and Ngerengere River in Morogoro imposed significant risks to environment and community health. The study found pH levels below their outfall to be as high as 12 (which exceeds the Tanzanian legal limit of 8.5), and levels of Chromium VI, a cancer-causing

chemical used in textile dying, at 75 times the legal limit [74]. Local health professionals report that this pollution has profound impacts for human health, especially children who regularly come into contact with the river water.

4.5. Introduced Species

Introduced species represent a widespread and growing challenge for Tanzania's freshwater systems. Fishes provide an example of this challenge. Numerous programs designed to improve food security or income through aquaculture and capture fisheries have been based on the introduced fish species [75]. Whereas these introductions have often targeted lake environments or are planned in off-channel facilities, introduced fishes have moved into nearby rivers either on their own or through human-mediated transport. Nevertheless, the extent to which introduced species have invaded riverine environments in Tanzania and the ecological and social consequences of their presence has received little study to date. For example, the well-known Nile perch (*Lates niloticus*) introduction into Lake Victoria has been linked by various studies to declines in native fishes and changes in socio-economic conditions in cities along the lakeshore [76,77]. However, the extent to which Nile perch have moved into the river systems that feed into Lake Victoria remains unknown. Residents of the Mara region in northwestern Tanzania have reported the presence of Nile perch in the Mara River, at least 10–15 km upstream from the lake (E. Anderson, unpublished data); the fish could be present in other river systems as well. Worldwide, tilapiine cichlids have been introduced in more than 140 countries, typically for aquaculture, and have established feral populations in at least 114 countries [78,79].

Tilapiine cichlids of the genus *Oreochromis* are found in freshwater systems throughout Tanzania, and many of them are important components of freshwater fisheries [12]. Whereas many *Oreochromis* species are native to Tanzania, others have been introduced, such as *Oreochromis leucostictus*. Even species native to Tanzania have been translocated beyond their original distributions and are now known to occur in other parts of the country in which they were not historically found; examples include *Oreochromis niloticus* and *Oreochromis esculentus*, native to Lakes Tanganyika and Victoria, respectively. A recent survey of *Oreochromis* distribution across Tanzania confirmed that these three species have colonized nearly all major river basins in Tanzania [75]. Studies of non-native *Oreochromis* from other tropical regions of the world have documented declines in persistence of native fish species in their presence, as a consequence of predation, competition, or habitat alteration [78]. In Tanzania, the introduction and translocation of *Oreochromis* also have been linked to biodiversity losses in native fishes. Here, the exotic *O. leucostictus* and the translocated *O. niloticus* have been shown to hybridize with the native *O. urolepis* in coastal rivers of Tanzania, thereby altering the genetic diversity of freshwater biota in these systems [23].

4.6. Climate Change

Finally, climate change will further complicate the management of freshwater resources presenting an additional impediment to equitable access to water in Tanzania. Shemsanga, Omambia and Gu [80] suggested that climate change will make rainfall patterns and the intensity of rainfall difficult to predict nationwide, which will affect Tanzania's rain-driven river systems. Although there is a paucity of studies quantifying the effects of climate change on the Tanzanian river basins, studies have predicted that the Rufiji River Basin—part of which is drained by the Great Ruaha River—will experience increased rainfall and therefore river flows, while the Wami-Ruvu River system will experience the opposite—decreased rainfall relative to historical patterns [81,82]. However, a more recent study, Gulacha and Mulungu [83] modelled climate change precipitation scenarios in the Wami-Ruvu and found a general increase in annual and monthly precipitation. Although Kangalawe et al. [84] support the hypothesis of increased rainfall within the Great Ruaha River basin with long-term rainfall records from 1980–2009 from the Iringa meteorological that show a slight increase over time, the high interannual variation have created a local perception of decreasing rainfall. Dessu and Melesse [85] modelled the hydrological changes in the Mara River Basin due to climate change and found an

increase in flow volume in future year ranges of 2046–2065 and 2081–2100 but cite growing water demand and interannual variation as a source of pressure for the basin. A more recent examination of the effect of climate change on the Mara River basin's hydrology, Roy et al. [86] also suggests more water availability within the rainy season because of increasing precipitation, but no substantial annual increase precipitation over the next 30 years. Again, the interannual variation is highlighted as the rainy season could produce peak flows but the annual precipitation does not show much alteration. Given the uncertainty inherent in addressing climate change, more studies across all catchments are needed to conceptualise the future water management scenarios and adequately address variation induced by climate change with attention to changes over seasons.

5. Recommendations for Future Efforts

In this paper, we have described the importance of Tanzania's rivers to sustain unique assemblages of freshwater, amphibious and terrestrial species, and to provide water to one of the fastest-growing human populations on earth. We have highlighted how legal and institutional frameworks around freshwater resources management offer some of the best support for river conservation, especially their prioritisation of ecosystem needs for water over most other off-channel uses. Nevertheless, the next decade will be critical for the future of Tanzania's rivers and their biodiversity, given the pressures of human population growth, agricultural expansion, proposed river alterations, introduced species and climate change. Existing legal and institutional frameworks may need to be revisited to meet the future consequences of these challenges. In light of the current status of knowledge on riverine biodiversity, emerging challenges and existing opportunities offered by water resources management frameworks—particularly experience and capacity around environmental flows—we offer three recommendations for future efforts towards river conservation in Tanzania over the next 10 years.

First, environmental flow assessments should be completed for remaining rivers in Tanzania and updated on 3–5-year cycles, given changes in land use, human population and climate that could affect the flows. Tanzania's NAWAPO and WRM Act provide the legal provisions for assessment and implementation of environmental flows, and there is high national capacity for flow-ecology research among Tanzanian scientists. Nevertheless, there is opportunity for expanding environmental flow assessments to include greater consideration of social relations and increased public participation, and to move beyond the current focus on securing only minimum flows [10,47]. These advances are in line with the revised Brisbane Declaration and Global Action Agenda on environmental flows, which recognized that social and cultural dimensions of environmental flow management warrant far more attention [45]. The Tanzanian Ministry of Water would be well poised for this task, given the large number of social scientists it employs and its experience with establishment of WUAs [43]. Greater incorporation of social considerations into environmental flow assessments may uncover hidden support for freshwater biodiversity conservation as well. For example, among aboriginal communities in northern Australia, river species such as fish or turtles are sometimes offered as special gifts, thereby mediating social relations (S. Jackson, personal communication). In other parts of Africa, there is belief in river Gods or spirits that need certain quantities of water [87]. These kinds of linkages between humans and riverine biota may be prevalent but undocumented in Tanzania. Strengthening the role of WUAs and increasing the recognition of traditional water management practices may uncover useful information to aid with environmental flow assessment and implementation [43,44].

Second, a national-level inventory of freshwater biota—focused on rivers—is urgently needed. More research on freshwater systems in Tanzania would expand available scientific knowledge for decision-making around water management, particularly water allocation. Currently, many existing environmental flow assessments and subsequent recommendations rely on the professional judgment—albeit based on years of natural history, ecological, or geomorphological research. More targeted studies on the relationships of riverine biota with river flow—especially for migratory, rare or endemic species—are needed to improve the understanding of ecological needs for water in terms of quantity, quality and timing of river flows. Priority for freshwater inventory studies could

be assigned to rivers like the Ruvu and Rufiji-Ruaha systems, which drain parts of the Eastern Arc biodiversity hotspot but also face increasing prospects for water diversions to support growing human populations in Dar es Salaam and Dodoma.

Third, we urge Tanzania to consider new frameworks for river conservation, such as freshwater protected areas, protected rivers, or assignment of legal personhood status to rivers. Currently, the network of protected areas in Tanzania is most aligned with terrestrial ecosystems and does not provide adequate coverage of rivers nor their biodiversity. For example, the river basin that contains the most extensive protected areas relative to basin size is the Great Ruaha; most Tanzanian river basins have <20–25% of their area overlapping with protected areas [13]. Traditional terrestrial-focused protected areas may not offer the best solution for river conservation. In response to similar challenges, new frameworks for river protection have recently taken root in many other countries. For example, freshwater protected areas recognize different zones within a river network, scaled geographically from critical areas where intense management or protection is needed, to river segments that have biological or cultural importance and may connect critical areas, to sub-basin or basin zones [88]. Costa Rica recently declared two rivers free flowing for the next 25 years, a decision partially influenced by the country's proliferation of hydropower development since the early 1990s and its national interest in biodiversity conservation [89]. Tanzania shows many parallels with Costa Rica as an international destination for nature-based tourism with a world-renowned system of protected areas, and it also still contains several free-flowing rivers [90]. In a new frontier for river conservation, Colombia, Mexico, India, and New Zealand have pursued an approach that grants personhood to rivers, meaning that a river must be recognized as an agent with life-giving force and offered legal representation [88]. Tanzania's explicit recognition of ecosystems as users of water in URT [2] and the WRM Act [3] could be bolstered by additional legal support for rivers, similar to these countries.

Beyond these specific recommendations, there is a need to build broad and increased awareness of the importance of freshwater systems and their biota in Tanzania. People in Africa and around the world are familiar with Tanzania's terrestrial ecosystems and wildlife—evidenced by widespread use of the Swahili word *safari* and common images of the Serengeti. Highlighting the critical role of freshwater ecosystems—particularly rivers—to wildlife survival could be an entryway for increasing recognition and public knowledge of Tanzania's freshwater systems, and hopefully stimulating more interest in their conservation.

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