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Review article

Rapid environmental flow assessment for sustainable water resource management in Tanzania's Lower Rufiji River Basin: A scoping review

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ABSTRACT

The use of Environmental flow (e-Flow) assessment is a widely adopted approach to facilitate informed decision-making concerning sustainable management and utilization of water resources in river systems. The Lower Rufiji River Basin faces various developmental pressures from several sectors, including hydropower, mining, agriculture, livestock, fishing, and tourism, necessitating effective management of the sub-catchment area to prevent significant environmental impacts. Consequently, it is essential to acquire a comprehensive comprehension of the catchment's attributes, encompassing both climatic and non-climatic factors. Supported by e-Flow batch analysis of the available data at Stiegler's Gorge using the global environmental flow calculator, a scoping review was conducted to determine the status of environmental flow in the lower Rufiji River basin. The findings suggest that, while there has been progress in understanding eFlow estimation, limited data and ecohydrological processes' poor comprehension still present challenges. Hydrological and holistic methodologies are commonly employed in Tanzania; however, uncertainties remain, raising questions concerning trust between decision-making tools and water resource utilization by the public. Climate variability influences e-Flow in the Rufiji River Basin, and the projections under various scenarios indicate an increased temperature, varying rainfall, and humidity levels. Further, the area has been identified as a vulnerable "hotspot" where communities face greater climate stressor risks. With the existing and planned developmental projects in the basin, including hydroelectric dams, mining, agriculture, livestock, and fisheries, it is critical to assess e-Flow in the Lower Rufiji River basin to ensure resource sustainability. Advocating for preserving a dynamic environmental flow regime in rivers is recommended, considering the Rufiji River Basin's habitat connectivity. The future research direction should be quantifying the contribution of base flow to the surface flow, and salinity dynamics in the Lower Rufiji River Basin, which can affect the Delta's biodiversity.

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1. Introduction

Increased population coupled with rapid increase in socioeconomic development to meet the rising demands of the population and climate change has imposed pressure on water resources [1]. Most developing countries are grappling with the overwhelming challenge of water resource management [2]. They face the difficult task of striking balancing between socioeconomic growth demands and preserving of a healthy water resource [3,4]. Moreover, these countries must also confront the additional challenge of effectively dealing with extreme events such as droughts and floods.

Comprehending and taking action on the interplay between water, energy, and agricultural food systems, community resilience, and climate change adaptation is a crucial aspect of sustainable development [5]. Historically, water has been predominantly managed from a supply-oriented perspective, prioritising short-term economic growth through its utilization [6]. Consequently, there has been lack of adequate consideration and limited understanding of repercussions stemming from excessive use or deterioration of river systems. For ecosystem integrity and or sustainability, it is crucial to maintain a specific volume of water flow with appropriate water quality [7,8]. This concept is commonly referred to as environmental flow (e-Flow) and is known by various names, such as instream flow needs, ecological reserve, ecological water demand, environmental water allocation (or requirement), compensation flow, or minimum flow [9]. An e-Flow is defined as "*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*" [10,11].

Although the concept of environmental water allocations, including e-flow, was recognized by the National Water Policy in Tanzania in 2002 [9,12], a study by Kashaigili [13], have highlighted several challenges associated with its implementation. In order to effectively allocate water flows to sustain the environment, it is essential to have access to comprehensive information on the quantity and quality of water resources within the basin. This understanding is crucial for making well-informed management decisions in catchments like the Rufiji River Basin, which provides essential ecosystem services for terrestrial and aquatic communities. However, the recent increase in anthropogenic activities, driven by the growing demand for energy and water in various sectors such as agriculture, livestock, domestic use, and wildlife, has intensified the pressure on ecosystem functions and services, including the e-flow.

The Rufiji River Basin in Tanzania is confronted with a range of pressing challenges, primarily influenced by human activities and the impacts of climate change [14]. Climate variability and change pose a significant risk, leading to an increased likelihood of droughts and floods [15]. Changes in land use, including expanding agriculture and urbanisation, further exacerbate the situation, causing soil erosion, habitat loss, and water quality degradation [16]. Moreover, large-scale projects such as damming, while offering benefits such as hydropower generation and water storage, also disrupt natural flow patterns and harm aquatic habitats [17]. Navigating the governance of natural resources in the basin is complex, requiring inclusive and equitable decision-making processes to balance the interests of various stakeholders.

Addressing these challenges necessitates a holistic approach. This entails implementing climate change adaptation strategies, promoting sustainable land use practices, and prioritising community engagement in decision-making processes. Strengthening governance structures and fostering stakeholder collaboration are vital components of sustainable resource management. Investing in scientific research and monitoring efforts will also contribute to a better understanding of the basin's dynamics and inform evidence-based management strategies. The Rufiji River Basin can strive towards sustainable development, resilience, and the preservation of its essential ecosystem services through concerted efforts.

One effective approach to assess and preserve flow regimes in the Rufiji River Basin is through conducting an Environmental Flow Assessment (EFA). Environmental flow plays a crucial role in ensuring water security and supports various aspects such as water supply, risk management, energy production, food security, livelihoods, economic development, community resilience, and climate change adaptation.

This scoping study aims to assess hydrological, climatological, geomorphological, ecological, and socioeconomic aspects within the basin, with a focusing on addressing gaps in previous initiatives in Tanzania, particularly the Lower Rufiji River basin. Climate change and human activities in ecologically sensitive areas like the Julius Nyerere National Park, Selous Game Reserve, Kilombero, and the Rufiji-Mafia-Kilwa Marine Ramsar Site are given special attention. It further examines the potential impacts of major development projects such as the Julius Nyerere Hydropower Project and other hydropower units like Mtera, Kihansi, and Kidatu. Key questions addressed include environmental flow regimes, effective assessment methods, climate-related effects on hydrology and ecology, integration of traditional knowledge and stakeholder perspectives, monitoring strategies, impacts of dam construction, and designing policies for safeguarding environmental flows in the lower Rufiji River Basin. By addressing these research questions, the study will gain insights into the current state of environmental flows, identify suitable assessment methods, understand the impacts of climate change, integrate diverse perspectives, and develop effective monitoring, mitigation, and policy strategies for managing eFlow in the Lower Rufiji River Basin.

2. Methodology

In order to create the most precise and valuable scoping study possible, great emphasis was placed on reviewing the most pertinent documents. The inventory review studies within our analysis encompass a defined period spanning from 1990 to 2023, nearly spanning three decades. This timeframe was deliberately selected to maintain relevance to the subject matter and to encapsulate the latest developments in the field. Our scoping review scope comprises prior studies, reports, and surveys conducted in the Rufiji River Basin, focusing on data collection and information acquisition crucial for the rapid assessment of e-Flow. We conducted an exhaustive search to guarantee the inclusion of the most pertinent and current studies within this specified scope. The study further consulted a

Global Environmental Flow Calculator (GEFC), which is supplied with the Global Database of simulated flow time series, which may be used as default hydrological data for Environmental Flow Assessment at a coarse spatial resolution of 0.5 by 0.5° (a collaborative project between IWMI and the Water Systems Analysis Group of the University of New Hampshire – http://www.wsag.unh.edu/).

2.1. Study area descriptions

The Lower Rufiji River Basin is located in the Southeastern part of Tanzania, covering an area of approximately 27,160 square kilometers with four sub-basins, contributing differently to a total runoff (Table 1). Diverse landscapes characterise it, including wetlands, floodplains, savannas, and forests. The sub-basin of the Rufiji Basin is home to a wide variety of wildlife, including large populations of elephants, hippos, crocodiles, and a range of bird species. Bordered by the Selous Game Reserve and the newly created Nyerere National Park, is home to a large number of endangered species, such as the African wild dog and black rhinoceros.

The Lower Rufiji River Basin, known for its vast floodplains (Fig. 1), is a home to a diverse array of flora and fauna. This is critical for Tanzania's development [19]. The Lower Rufiji Basin is the home key transportation route in the region and an agricultural hotspot in which the most grown crops include rice, maize, and beans. Fishing is also an important economic activity, with many communities relying on the Lower Rufiji River Basin for their livelihoods. Due to this ecological sensitivity and the aforementioned existing challenges, there is need to monitor, and promote conservation. Fig. 2 shows a hypsographic curve of the total catchment, a curve showing area-elevation relationships along the main thalweg, and hypsographic curves for major catchment units in sequence.

2.2. Climatic characteristics

The climate of Rufiji basin varies from the coast to the highlands. The climate is humid and hot on the coast and the Kilombero valley, while the Northwestern part of the Great Ruaha River Basin is hot and dry. In the mountainous regions, the climate is cold. Most of the Rufiji Basin, especially on the eastern and western sides, experience higher temperatures of 28–31 °C, while certain areas may even see temperatures reaching 31–34 °C. The largest portion of the basin experiences unimodal rainfall, the majority falling from November to May [22]. The Lower Rufiji River Basin faces a range of challenges, including deforestation, soil erosion, and water pollution [23]. Climate change is also a growing concern, with the region experiencing increasingly erratic weather patterns and more frequent droughts and floods.

The Standard Precipitation and Evapotranspiration Index (SPEI) trend also shows severe wetness and dryness occasions persist in the catchment. SPEI is a relative measure of surface water surplus or deficit with respect to hydroclimate conditions of the reference period. Thus, the results of surface water deficit may be interpreted as dryness or, in other words, an indicator of drought conditions. As SPEI is a normalized index, an SPEI value of zero would indicate no change relative to historical values. Positive two (+2) would indicate extremely wet, and negative two (−2) indicating extremely dry (Fig. 2). Fig. 3 shows years of dry and wet years/seasons enough to tell the status of flow variability in the river basin. In addition to the findings, some other researchers have identified vulnerability hotspots in the Lower Rufiji river basin [24].

2.3. Projected climate

It is just like Fig. 4A and B, and Fig. 4C as generated from http://climexp.knmi.nl/plot_atlas_form.py, highlight the projected climate under different Representative Concentration Pathways (RCPs) in the Rufiji River Basin. These RCPs (RCP2.6, RCP4.5, RCP6, and RCP8.5) are based on different assumptions about future population growth, economic development, energy use, and land use patterns. They are used in climate models to project potential future greenhouse gas concentrations in the atmosphere. The numbers in the RCPs refer to the radiative forcing level (in watts per square meter) that the scenario is expected to produce by the year 2100. For instance, RCP2.6 represents a low-emissions scenario, while RCP8.5 represents a high-emissions scenario.

On the left, for each scenario, one line per model is shown plus the multi-model mean; on the right, percentiles of the whole dataset: the box extends from 25 % to 75 %, the whiskers from 5 % to 95 %, and the horizontal line denotes the median (50 %).

3. Methods for assessing environmental flows

Several frameworks, and or methods (Table 2) for assessing environmental flows for rivers that have been researched and applied in different localities [25,26]. However, there is no single best method for conducting an environmental flow assessment [6], and there

Table 1
Description of the sub-catchments for the whole of Rufiji River Basin (*Source* [18]).

Rufiji Basin Catchment Area				
River catchment	Area km^2	Percentage of area	Mean runoff (billion cubic meter/year)	Percentage of run-off
Great Ruaha	83,970	47	3.3	15
Kilombero	39,990	23	13.8	62
Luwegu	26,300	15	4	18
Rufiji (lower river)	27,160	15	1.1	5
Total	**177,429**	**100**	**22.2**	**100**

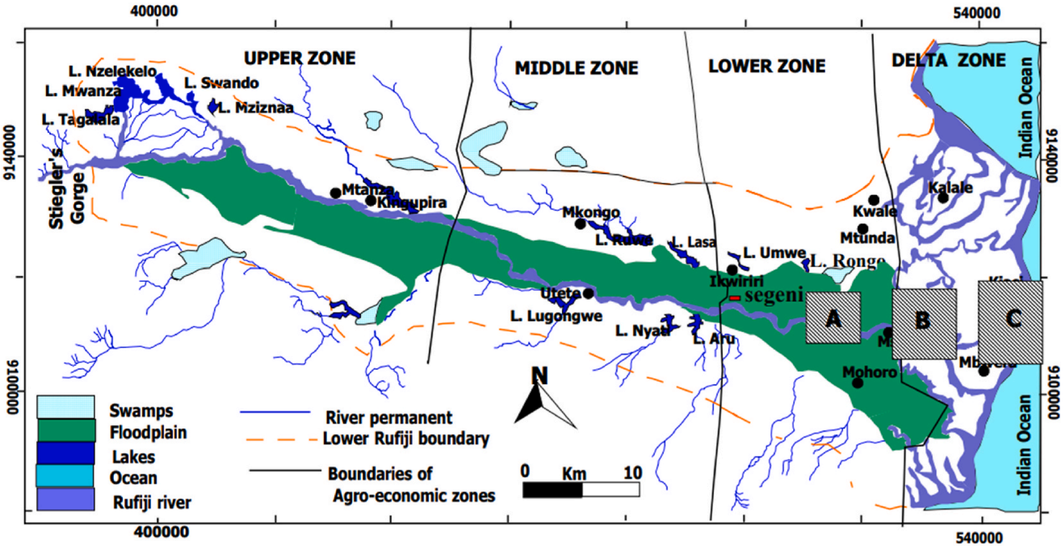


Fig. 1. Map showing a Lower Rufiji sub-catchment (*Source* [20]).

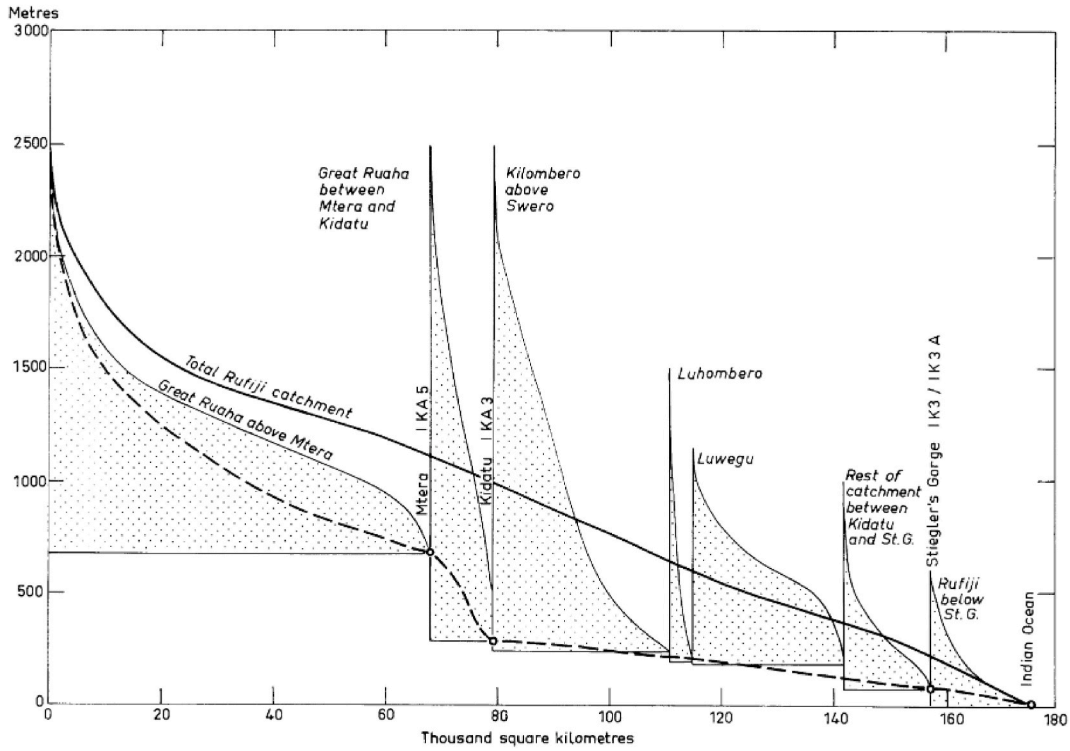


Fig. 2. Hypsographic analysis of the Rufiji basin (*Source* [21]).

are uncertainties [27]. Specific method and approaches depend on issues to be investigated and the resources available, including monitoring data.

Tharme [25] grouped the methodologies into hydrological, hydraulic, habitat simulations, and holistic methodologies. Hydrological and hydraulic models, for instance, simulate river flow patterns such as velocity, volume, and duration and estimate the impacts of flow regulation on the ecosystem/against the needs of aquatic habitats and biotic communities. Habitat methods use the physical characteristics of a river, such as channel geometry and substrate type, to estimate the amount of suitable habitat available for different aquatic species/in response to changes in flow regime. Besides conventional methods, rivers have been intensively studied and modelled via machine learning and are ever-increasing and ubiquitous in numerous research fields, although there are still questions

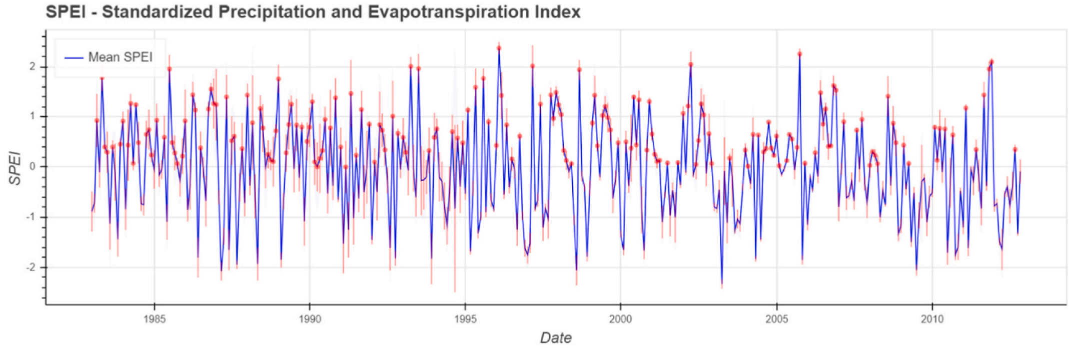


Fig. 3. Mean Standardized precipitation and evapotranspiration index (SPEI). Provider: Vrije Universiteit Amsterdam (retrieved from https://wci.earth2observe.eu/portal/?).

about their actual impacts [28]. These computer algorithms. Recently, unsupervised learning and supervised learning have dominated the field of river research, although their proportion has decreased over the last decades, while deep learning and big data analytics have gained little popularity [28].

3.1. Limitation of different categories of e-flow methodologies

Some previous studies [29,30], indicated advantages and disadvantages of different categories of e-flow calculation methods, including hydrology, hydraulic, habitat simulation and holistic methods. A general aspect could be advancement in technologies and rapid evolution resulting from environmental degradation [26]. Although each category has its benefits, hydrological methods, for example, suffer from low accuracy primarily due to a singular factor. Hydraulic methods, on the other hand, fail to capture seasonality and demand an extensive dataset of river topography. Habitat simulation methods, while useful, are constrained by a limited focus on river biological species and struggle to provide a holistic view of the river ecosystem. Meanwhile, Holistic methods, which aim for a comprehensive approach, are burdened by the necessity of substantial data support and intricate calculations [29]. In light of these limitations, numerous scholars [29,31] propose the combination of multiple methods as a means to address the shortcomings of a single method.

A combination of methods can be used to provide a more comprehensive assessment of environmental flows. This is accommodated under the holistic methodology (e.g., Building Block Methodology). The modified building block methodology has been used due to its simplicity [18] and commended for use in Tanzania [32]. This corroborate the observation of the World Meteorological Organisation report, which noted hydrological and holistic methods being among the most used in Tanzania and that the country can be seen as the leading example in Africa [9]. The BBM approach is based on the idea of breaking down a river or stream system into smaller, more manageable units, or “building blocks,” and assessing the flow needs of each individual unit. The methodology typically involves the identification of the building blocks whereby the river or stream system is divided into smaller units based on physical, hydrological, and ecological characteristics. This is followed by assessment of flow requirements, integration of building blocks, and Implementation. The building block methodology is a flexible and adaptive approach that can be tailored to the specific characteristics and needs of a given river or stream system. It is widely used in the assessment and management of environmental flows worldwide.

3.2. Establishing environmental flow requirement

Environmental flow requirements refer to the amount of water that needs to be maintained in a river or stream to sustain the health and function of the ecosystem. Establishing environmental flow requirements in the lower Rufiji River would involve studying the baseline information on basin characteristics, climate, river’s hydrology, ecology, geomorphology, and socioeconomic activities [33]. This baseline information would be used to determine the flow regimes (patterns of flow) and water levels that are necessary to support the various ecological and human uses of the river. Factors that may be taken into account when establishing environmental flow requirements could include the needs of fish and other aquatic species, the health of riparian (riverbank) vegetation, the availability of water for other human uses, including irrigation and or storage, and the potential impacts of climate change on water resources in the basin of interest.

3.3. Lithology

The Geomorphology of the Lower Rufiji River Basin is among the components that make the uniqueness of the Rufiji River Basin (Fig. 5). The LRRB can be classified as lowland with flood plains, alluvial plains lacustrine depressions, coastal and delta plains [22]. This is in agreement with Shagude [34], who further clarify that the geomorphological history of the LRRB can be classified as flood plain covered and alluvial soils and where flood inundation occurs, Delta where in addition to flood inundation, seawater intrusion became important, and the terrace area which is developed on an old sedimentary complex consisting of sands.

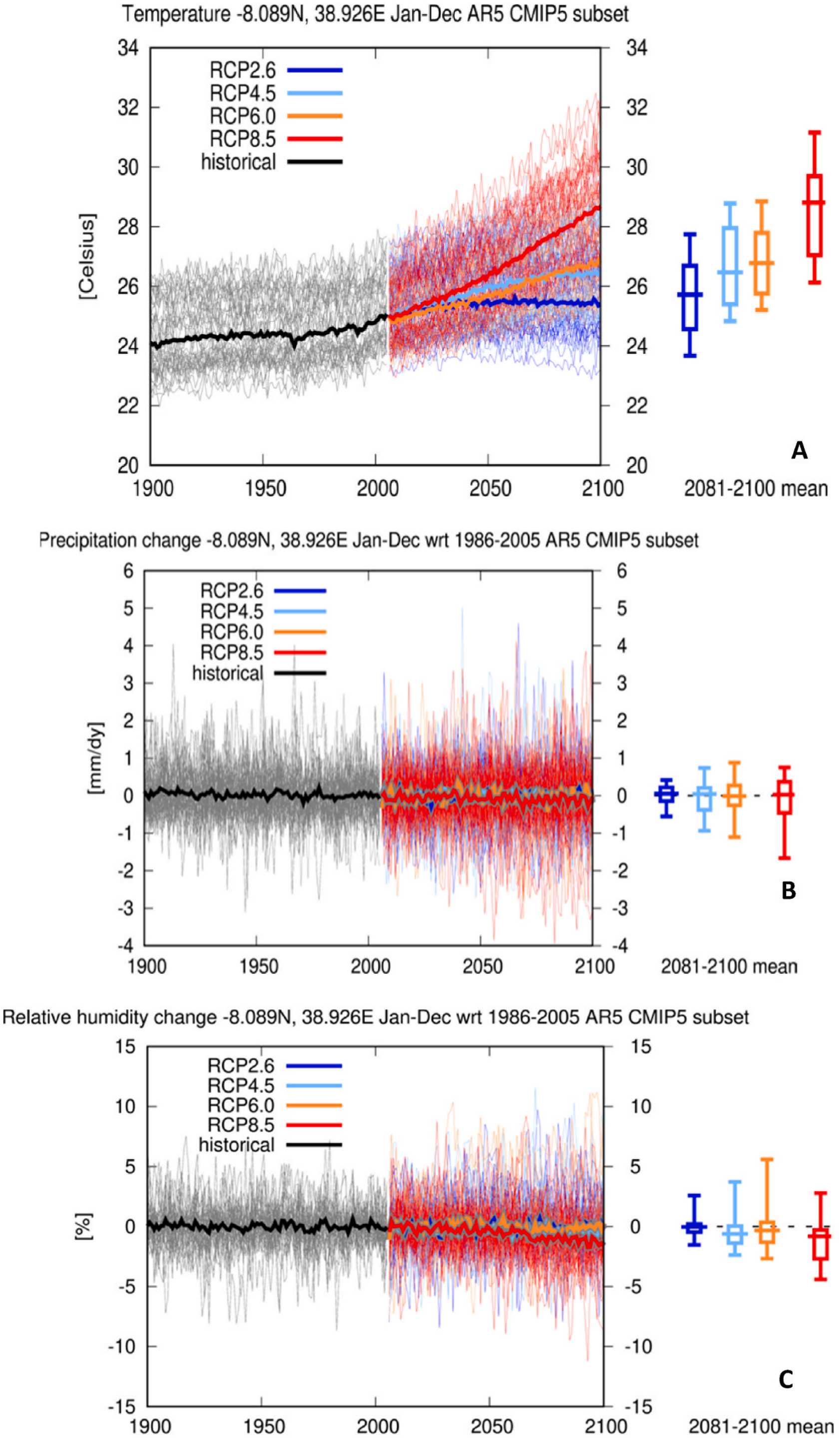


Fig. 4. Temperature (A), precipitation (B), and relative Humidity (C) changes at −8.089 N, 38.926E for January–December with respect to 1986–2005 from the Intergovernmental Panel for Climate Change (IPCC)'s Fifth Assessment Report (AR5) relies heavily on the Coupled Model Intercomparison Project, Phase 5 (CMIP5) subsets (*Source:* http://climexp.knmi.nl/plot_atlas_form.py).

3.4. Rufiji river hydrology

Rufiji river basin has an annual flow of 800m3/s. The flow is contributed from three tributaries of Luwegu, Great Ruaha, and Kilombero at ratios of 15 %, 18 % and 62 %, respectively [36]. The flow varies depending on the season of the year, with mean

Table 2
Classification of environmental flows assessment methods (*Source:* [26]).

Organization	Categorization of Methods	Sub-category	Example
International Union for Conservation of Nature (IUCN) as cited in (Dyson et al., 2003)	Methods	Look-up tables	Hydrological (e.g., Q95 Index) Ecological (e.g., Tenant Method)
		Desktop analyses	Hydrological (e.g., Richter Method) Hydraulic (e.g., Wetted Perimeter method) Ecological
		Functional analyses	Building Block Methodology (BBM), and expert panel assessment benchmarking methodology
		Habitat modelling	
	Approached		Expert Team Approach Stakeholder Approach (expert and non-expert
	Frameworks		Instream Flow Incremental Method (IFIM), and Downstream Response Imposed Flow Transformations (DRIFT)
World Bank as cited in (King and Brown 2003)	Prescriptive approaches	Hydrological Index methods	Tennant Method
		Hydraulic rating Methods	Wetted Perimeter Method
		Expert Panel	
		Holistic approaches	BBM
	Interactive Approaches		IFIM, DRIFT
International Water Management Institute (IWMI) as cited in (Tharme, 2003)	Interactive approaches		IFIM, DRIFT
	Hydrological index methods		Tenant method
	Hydraulic rating methods		Wetted perimeter Method
	Habitat simulation methodologies		IFIM
	Holistic Methodologies		BBM, DRIFT, Expert Panels, and benchmarking Methodologies

minimum flows (200 m3/s) occurring during the dry seasons and mean maximum flows (2000 m3/s) in the wet season [21,36]. For the studied in the past in Rufiji River Basin studied (for the available data) indicates that about 250–300 million tons of suspended sediments have passed through Stiegler's Gorge for 16 years, covered by discharge records [21].

3.5. Rufiji river ecology and ecosystem services

The ecology of the lower Rufiji River is likely to be complex and varied, with a range of plant and animal species living in and around the river. The specific types of species present in the lower Rufiji River depend on a variety of factors, including the physical and chemical characteristics of the river and its surrounding environment, the availability of food and other resources, and the presence of any natural or human-made disturbances. Some of the ecological features that are found in the LRRB include aquatic plants, fish, birds, mammals, riparian, and In-stream zones. Both riparian and in-stream vegetation play important roles in the ecology of the LRRB. Riparian vegetation helps to stabilize the riverbanks, prevent erosion, and provide habitat for a variety of animal species. It also helps to filter pollutants and sediments from runoff before they enter the water, improving water quality. In-stream vegetation provides aquatic animals a habitat, and helps to stabilize the riverbed and regulate water flow.

A recent survey by the Ministry of Natural Resources and Tourism [37] surveyed the LRRB near Stiegler's Gorge (see Fig. 6) and found the followings.

For the vegetation, 306 plant species (trees, shrubs, herbs, grasses, sedges, and climbers) were identified in and outside the project impact area. Trees contributed 52 % (34 plant families); shrubs and climbers 32 % (21 plant families); grasses and sedges 3 % (2 plant families); and herbs 43 % (28 plant families) of all the recorded plant species. In general, species from the family Leguminosae contributed most to the total number of species (23 % with 73 species), followed by the family Graminae (11 % with 35 species) [37].

The assessment found that 45 species of large mammals were found in 21 families within 11 orders (large ungulates). In addition, out of 64 terrestrial large mammal species of the former Selous Game Reserve (SGR) were identified in and outside the Julius Nyerere Hydropower project area. Regarding small terrestrial Fauna, a total of 226 species were identified (13 species of small mammals-rodents, 190 species of birds, 11 species of amphibians, 5 species of reptiles, and 7 species of ground arthropods/invertebrates). About aquatic plants (macrophytes), twenty-two (22) species belonging in 15 plant families were identified in the study area. The most frequently occurred species were *Pistia stratiotes* (40 %), *Nymphae* sp (27 %), *Mimosa pigra*, *Echnochlea* sp, *Cyperus articulates,* and *C. imbricatus* contributing 13 % each [37].

On the aquatic resources, 34 species of fish from 12 families have been sampled, of which six has not been identified to species level. *Citharinus congicus* were most abundant (28 %, 492 counts) compared to other fish species encountered in the project area followed by *Oreochromis urolepi* 82 (15 %, 259 counts), *Labeo congoro* (9 %, 165 counts) and *Synodontis rufigiensis* (9 %, 164 counts). The rest of the fish species constituted 39 % of the total. Eighteen (18) species of phytoplankton were also identified. The most dominant species were *Microcystis flos-aguae* (62 %), *Aulocoseira* spp (20 %), and *Pediastrum duplex* (8 %). The rest of species comprises 6 % of the total. While fifteen (15) families from eight orders of macroinvertebrates were identified, *Atyiidae* sp. appears to be the most abundant and

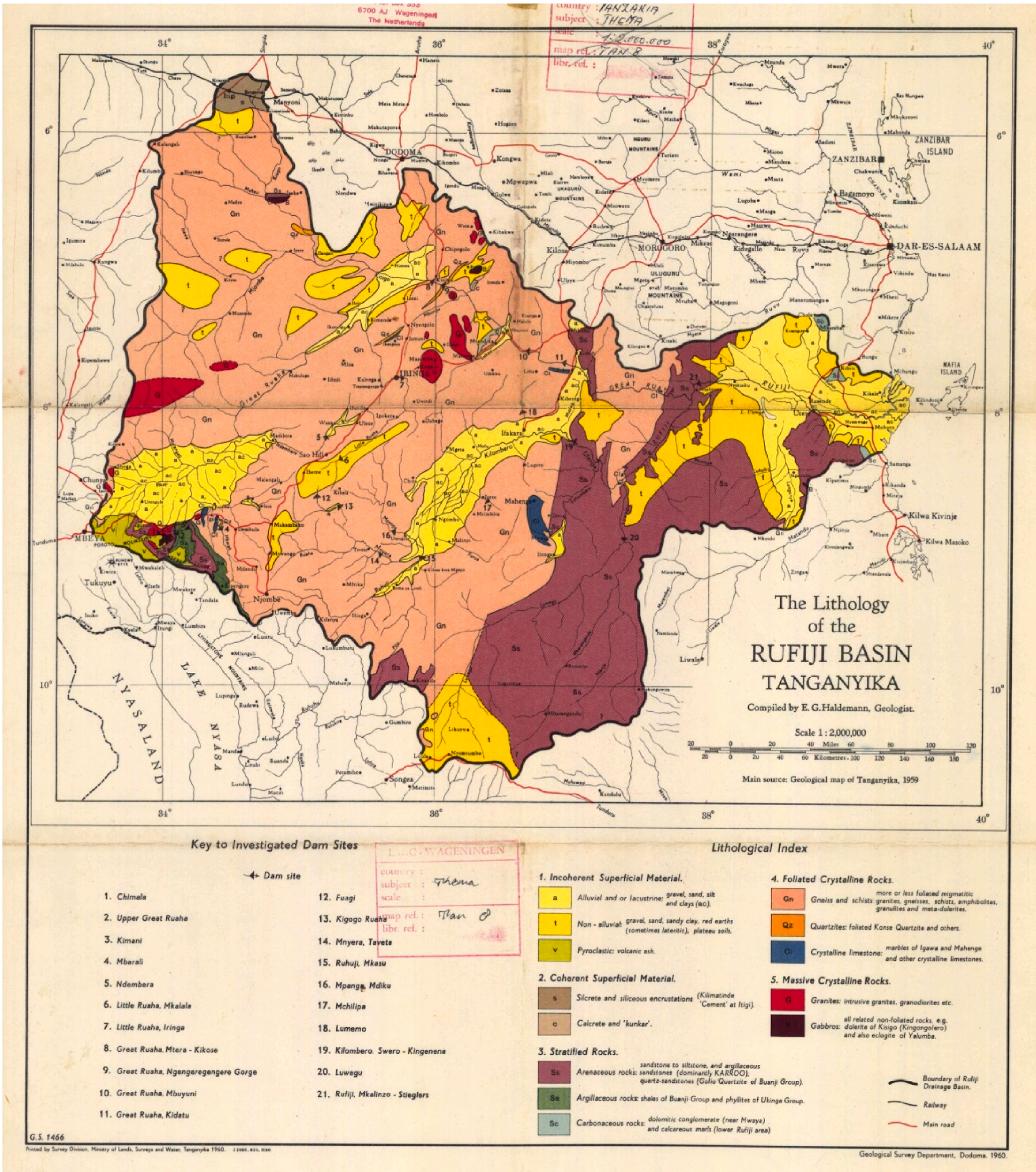


Fig. 5. Lithology of the Rufiji basin *(Source:* [35]*).*

dominant family comprising 41 % followed by *Hydrophilidae* Sp. (23 %) [37]. Overall, the ecology of the LRRB is likely to be dynamic and complex, with a range of species interacting with each other and their environment in a various of ways.

Ecosystem services are the benefits that humans receive from the natural environment. The Rufiji River Basin (RRB), provides a wide range of ecosystem services that are essential for human well-being and economic development [38,39]. Some of the ecosystem services provided by the RRB may include water provision, flood control, pollution control, ecotourism, soil formation, and climate regulation. The vegetation in the riparian zone and the macroinvertebrates in the water column help to filter pollutants and sediments from runoff, improving water quality. Others include Habitat, Climate regulation, and Recreational opportunities. It is important to

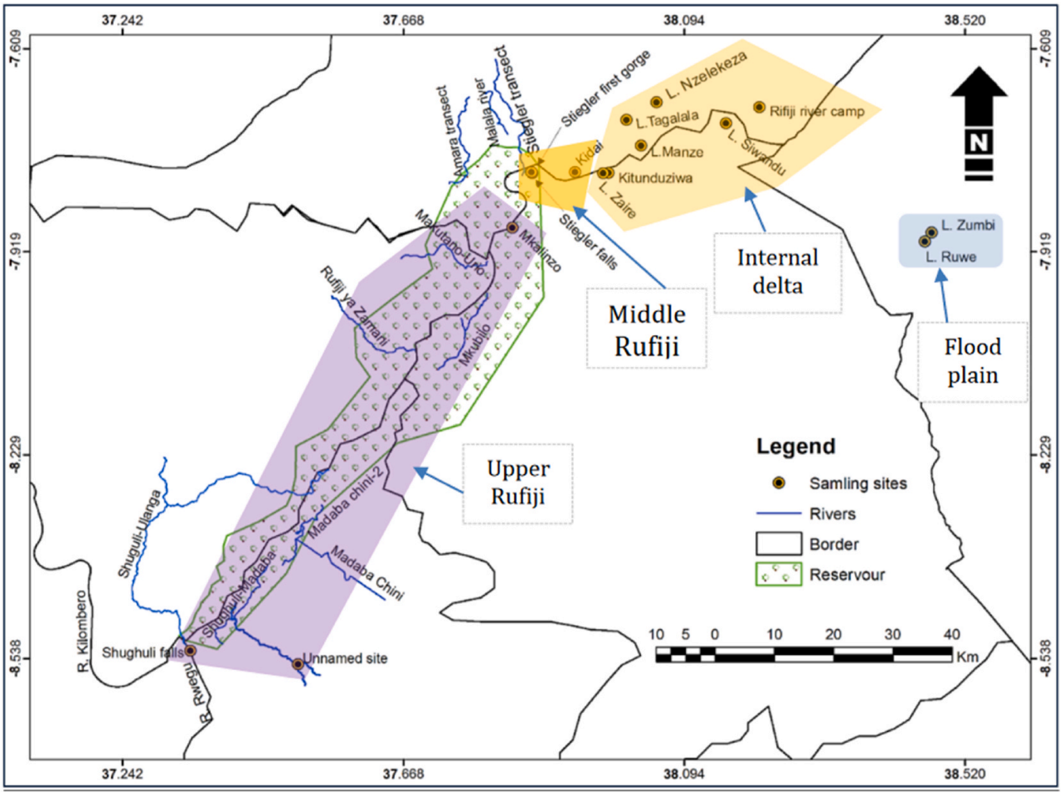


Fig. 6. A map of sites surveyed during the baseline study by the Ministry of Natural Resources and Tourism *(Source* [37]*)*.

recognize and value the ecosystem services provided by the RRB in order to ensure their long-term sustainability. This may involve implementing policies and practices that protect and preserve these ecosystems, such as land use planning, pollution control, and habitat restoration.

3.6. Basin social and economic activities basin

The RRB is an important economic and social resource for the people who live in the region. Major economic activities in the RRB include energy production and transmission, agriculture (inducing livestock keeping), fishing, forestry services and products, mining, and tourism [40]. Changes in the environmental flow of the Rufiji River have profound social and economic consequences for local communities that rely on the river for their livelihoods. We will explore the impacts of these changes on various aspects, including local communities' dependence on the river for water supply, fishing, and agriculture. The study will also discuss the disruption of traditional practices and cultural values, as well as the vulnerability of communities to changes in water availability and quality.

3.7. Energy production

On the hydrology, the Rufiji River Basin is characteristically large, with high rainfall and low evaporation rate, which results in a high river flow and a large amount of water discharge into the Indian Ocean. It originates in the highlands of the southern part of the country and flows through several kilometres before reaching its delta in the Indian Ocean. The river and its tributaries support significant agricultural, industrial, and domestic water uses and significant biodiversity in floodplain ecosystems and wetlands. The hydrology of the Lower Rufiji River Basin is influenced by factors such as rainfall patterns, land use, and human activities such as dam construction, irrigation, and groundwater extraction.

The Rufiji River Basin is home to several large dams, including (i) Julius Nyerere Hydropower Dam (the then Stiegler's Gorge Dam): This dam is currently under construction in the Rufiji River Basin. When completed, it will be the largest dam in Tanzania and will have a capacity of 2115 MW; (ii) Kidatu Dam: This dam is located on the Kidatu River, a tributary of the Rufiji River. It was built in the 1970s and has a capacity of 240 MW; (ii) Mtera Dam: This dam is located on the Mtera River, another tributary of the Rufiji River. It was built in the 1980s and has a capacity of 140 MW. Others are Mpanga, Kihansi, and Ruhudji [41]. These developmental projects and other interventions are argued to be able to cope with changes in hydro-climatic variability [42].

These dams are used primarily for hydroelectric power generation, and other associated benefits such as irrigation, and flood control in the downstream. However, they might also have potential impact on the river ecosystem, including altering water flows, so regular monitoring of their impact is necessary. Understanding RRB's resources and the fact that Tanzania has unused profitable potential as a percentage of total electricity generation [43], it is wise to integrate environmental flow in these developmental projects.

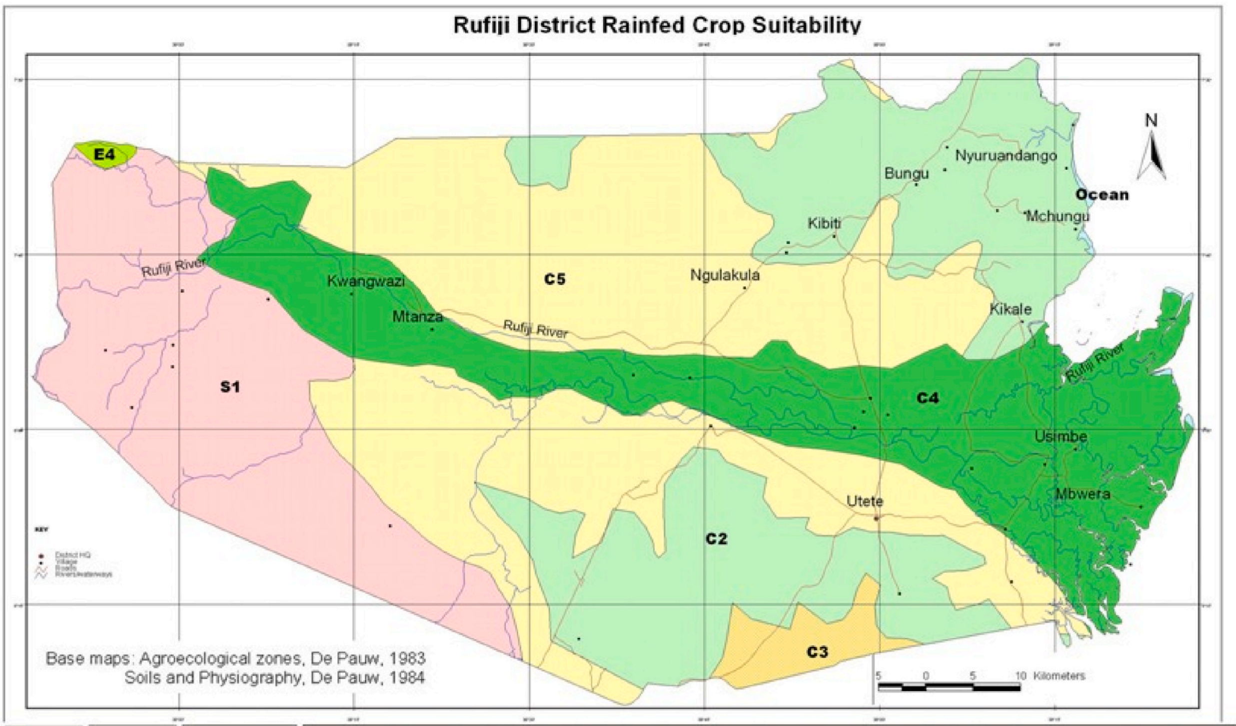
3.7.1. *Integrating environmental flow in dam design and development*

As stated earlier, environmental flow is the amount of water that is required to maintain the health of a river or stream ecosystem. Alteration of the river's natural flow by damming is a worldwide scenario [44]. When designing and developing a dam, it is important to consider the environmental flow requirements of the area in order to minimize negative impacts on the local ecosystem [45]. One way to integrate environmental flow into dam design and development is with environmental flow releases. These releases allow for a certain amount of water to be released from the dam at specific times in order to mimic natural flow patterns and support the needs of the local ecosystem.

Another way to integrate environmental flow is with fish passes or other measures to allow for the migration of fish and other aquatic species. This can help to maintain the biodiversity of the area and ensure the long-term health of the ecosystem. Overall, incorporating environmental flow considerations into dam design and development can help to minimize negative impacts on the local environment and ensure the sustainable use of water resources.

Even with the best available expert knowledge and analysis, dam developers, governments, and stakeholders need to understand that the environmental consequences of hydropower dam development and operations cannot be predicted with complete certainty. To be ecologically and socially sustainable, water and energy development and management need to be perpetually informed by monitoring, carefully targeted data collection and research, and further analysis to address new uncertainties or surprises. Therefore, a program of monitoring, evaluation, and adjustment commonly referred to as adaptive management should be fully and explicitly integrated into any hydropower development or reoperation plan so that management approaches can be continually modified in response to increased understanding or changes in human or ecosystem conditions. The economic risks from uncertain future environmental constraints need to be addressed explicitly as part of an adaptive management strategy [42].

With hydropower project for example, four critically important points apply to both single-purpose and multiple-objective hydropower projects: (i) Ecosystem-based objectives that address biodiversity and ecosystem service protection should be an integral aspect of planning efforts at all levels of governance and decision-making. When considering trade-offs among alternative planning



AEZ Code	Altitude masl	Rainfall mm/year	Crops Suitable per Agroecological zone
C2	<500	800 - 1000	Cashew, coconut, mango, maize, s/potato, cassava, simsim, cow pea, p/pea, lablab, ground nut, passion fruit, millet, sisal, jatropha, sunflower, tobacco, cotton
C3	<500	800 - 1000	Cassava, mango, cashew , coconut, sorghum, cow pea, s/potato, passion fruit, cow pea, p/pea, sisal, jatropha
C4	<200	1200-1400	Rice, sugar cane, coconut, maize, millet, cow pea, p/pea, s/potato, cotton, mango, passion fruit, sisal, citrus, cashew, ground nut, pine apple, banana, cassava
C5	<200	1000-1200	Rice, cassava, maize, cashew, coconut, millet, sorghum, cow pea, p/pea, citrus, s/potato, cotton, mango, ground nut, simsim, passion fruit, sisal, pine apple, sunflower, tobacco
E4	200-1000	800 - 1000	Maize, sorghum, coconut, cassava, s/potato, cow pea, p/pea, ground nut, simsim, soya bean, sunflower, tobacco, cotton, millet, sisal, jatropha
Ocean			Water body
S1	200-500	800 - 1000	Sorghum, maize, cassava, tobacco, s/potato, millet, cow pea, p/pea, lablab, mango, passion fruit, cashew, coconut, simsim, sunflower, cotton, ground nut, sisal

Fig. 7. Rufiji District soil map.
Source (https://www.kilimo.go.tz/maps/Rufiji_Crops_Suitability_Map.jpg)

scenarios, the consequences for ecosystem-based benefits need to be explicitly articulated and considered; (ii) It will be far easier and more cost-effective to integrate environmental flow considerations into the planning and design of hydropower schemes than to modify or retrofit the design and operation of existing schemes; (iii) Environmental flow needs can and should be considered in every stage of a hydropower development project, including location (or siting) of dams, dam design, dam, and reservoir operations, and reoperation (or changing existing operations); and (iv) It is important to design hydropower schemes with built-in flexibility to accommodate changes in socioeconomic and environmental demands, market conditions, changing technologies, and climate change [45].

3.8. Agriculture, fishing and livestock

The dependence on the Rufiji River for water supply, fishing, and agriculture is significant for local communities. Agriculture is likely a major source of livelihood for many people in the lower Rufiji River Basin. The fertile floodplains of the Lower Rufiji River provide ideal conditions for growing crops such as rice, sugarcane, and maize (see Fig. 7). Fishing is also an important activity in the RRB, as the River is home various fish species [23]. The productive lands attract influx of both people and associated economic activities.

Livestock keeping is a significant economic activity in the Rufiji River Basin. Local communities keep cattle, goats, sheep, and poultry, mainly for meat and milk production. Livestock also provides an important source of income through the sale of animals and animal products. With the current pressure of migration of livestock from other parts of the country (Fig. 8), the state of the LRRB may change completely in the near future. It might lead to conflicts and occasionally even violence, especially concerning the distribution of land and water resources [46,47]. Therefore, it is essential to consider these impacts when making decisions regarding water resource management and development projects in the region. Implementing sustainable and inclusive approaches that address the needs and perspectives of local communities can help mitigate the negative consequences and support their livelihoods amidst changing environmental conditions.

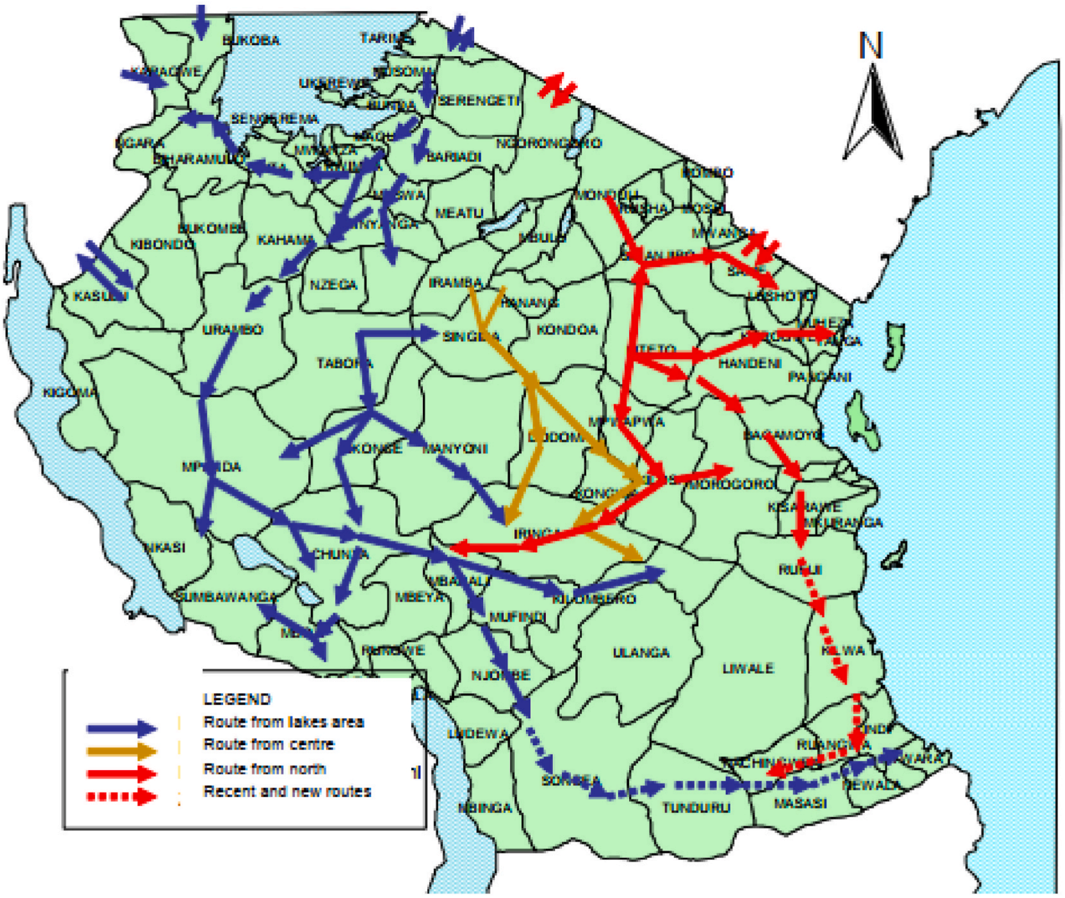


Fig. 8. Pastoralist migration in Tanzania (*Source:* [47]).

3.9. Tourism and mining

Tourism is also a significant income-source at the national level through a Gross Domestic Product (GDP) and locals in the Rufiji River Basin. Tourists are attracted by the natural beauty of the landscape and the opportunity to view wildlife, such as elephants, Nile crocodiles, and other large mammals, in their natural habitats. In Rufiji, a recent amendment of creating a Nyerere National Park will likely attract migration of people and other allied services.

On Mining, Rufiji River Basin also has a variety of deposits of hydrocarbons [48] and minerals including gold, coal, and uranium [40]. Mining activities by both large-scale mining companies and artisanal miners (Chunya/Morogoro) provide employment opportunities and revenue to the local and national governments. In the Catchment, Mahenge Graphite and Mkuju (Uranium One's) projects are the most advanced mining projects. In 2013, it became the first uranium mine to receive a licence from Tanzania's ministry of Energy and Mineral Resources. These projects, inducing other minor ones (small-scale miners) cumulatively, are likely to pose potentially significant impacts on the environment once active.

3.10. Land use/changes in the Rufiji river basin

Land use/changes in the whole basin have been increasing at a rate of 6.3 % in cultivated land per year [49]. Recent reviews findings have indicated that the reasons for such an increase in the degradation rate are associated with conversion of natural vegetation, including agriculture, settlements, grazing, uncontrolled fires, and unplanned land uses [50]. Fig. 9 (A and B) shows a land use status in 2013 and the projected (2025) one.

4. Simulated water balance at Stiegler's Gorge

A simulation of water balance by Hamisi [52] in the LRRB showed that 55 % of accumulated precipitation is lost through evapotranspiration and 42 % is river runoffs for downstream agriculture and ecosystem services. The study further demonstrates the linkage between flooding and smallholder farming systems and average water levels at times and in a specific location in the Lower Rufiji River basin (see Fig. 10). Hilly and highest terrace farming are adaptive mechanisms during heavy rainfall and peak floods. This could be among the adaptive strategies in the basin. According to this particular study, this normally occurs during the April–May months which falls in the long-rain seasons countrywide.

A study by Ref. [18] established environmental flow requirements for the Kilombero River valley with further consideration of the future eFlow needs for the LRRB and its floodplain. This particular study recommends regular reviews of the environmental flows in the RRB in consideration of future definition of the flow requirements of the Lower Rufiji Sub-Basin. The report further highlights some of the main social-ecological justifications for establishing environmental flow recommendations in the Lower Rufiji River Basin.

From the GEFC tool, for example, the summary of environmental Flow at Stiegler's Gorge covering the period of 1901–2000 and preliminary findings are given in Fig. 11A. The Flow indicates that the high flows are during the months of March, April, and May, which are normally long rains seasons. The mean annual runoff (MAR) is at 62322 million Cubic meters (MCM). The percentages for environmental Management Classes from MAR are also indicated, and the subsequent validation are available at https://eflows.iwmi.org/(Fig. 11B).

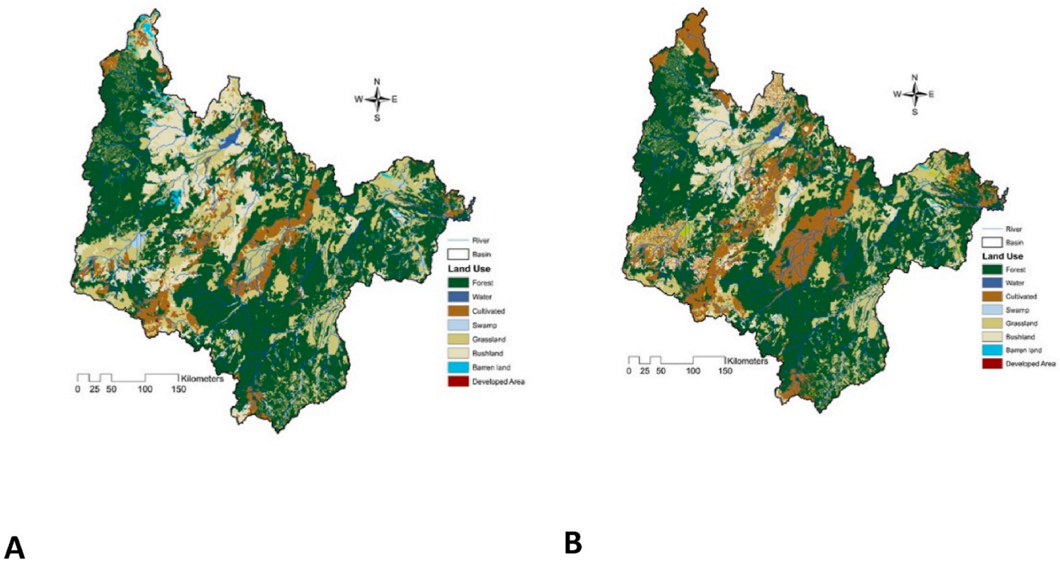


Fig. 9. Land use in 2013 (A) and projected land use in 2025 (B) *(Source:* [51]*)*.

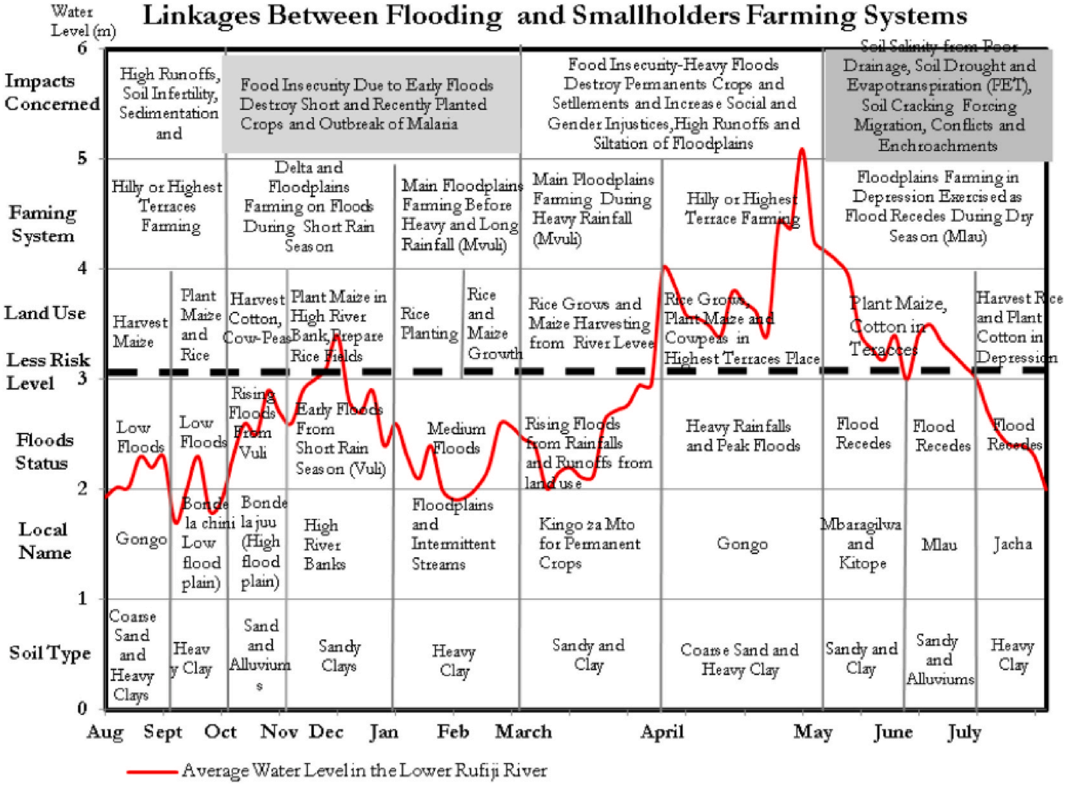


Fig. 10. Average water Level and linkage to the flooding and smallholders farming systems in the Lower Rufiji River *(Source* [52]*)*.

4.1. Consequences of changes in environmental flow for lower Rufiji river

Changes in the environmental flow of the Rufiji River have significant social and economic consequences for local communities that depend on the river for water supply, fishing, and agriculture. These consequences have the potential to disrupt their livelihoods and overall well-being. Several studies have examined the effects of changes in environmental flow on communities and provided insights into the potential consequences. Some of these consequences are further discussed.

4.2. Disruption of traditional practices and cultural values

The alteration of the Rufiji River's environmental flow due to climate change and water over-water abstraction has a significant impact on the traditional practices and cultural values of the local communities [53]. This disruption affects various aspects of their lives, such as livelihoods, agriculture, fishing, and religious ceremonies. Reduced water availability leads to decreased agricultural productivity, affecting traditional farming practices and food security. Changes in water levels and flow patterns also affect fish populations and migration patterns, resulting in decreased fish catches and disrupting traditional fishing practices. The river holds sacred value for the communities, and any changes in its flow have profound impacts on cultural values and or changes in a well-established historical social construct [36]. To mitigate these disruptions, it is crucial for policymakers and stakeholders to consider local perspectives and involve them in decision-making processes. Other recommendations can be the use of well-established theories and toolkits for informed decision-making [54].

4.3. Vulnerability to changes in water availability and quality

Changes in the environmental flow (whether natural or manmade) of the Lower Rufiji River have the potential to profoundly affect local communities and their livelihoods by altering water availability and quality [55]. Such alterations can lead to increased vulnerability and pose challenges for various sectors dependent on the river. Reduced water availability can restrict access to water for domestic use, agriculture, and livestock rearing, threatening food security and livelihoods. It can also lead to conflicts among different user groups and affect community cohesion. Additionally, shifts in water quality due to changes in flow patterns can render the water unfit for consumption, irrigation, or other productive uses, leading to waterborne diseases and affecting community health. The agricultural sector is particularly affected, with disruptions in irrigation systems, reduced water availability for crop cultivation, and increased vulnerability to food insecurity. Fishing communities relying on the Lower Rufiji River also face negative consequences, such

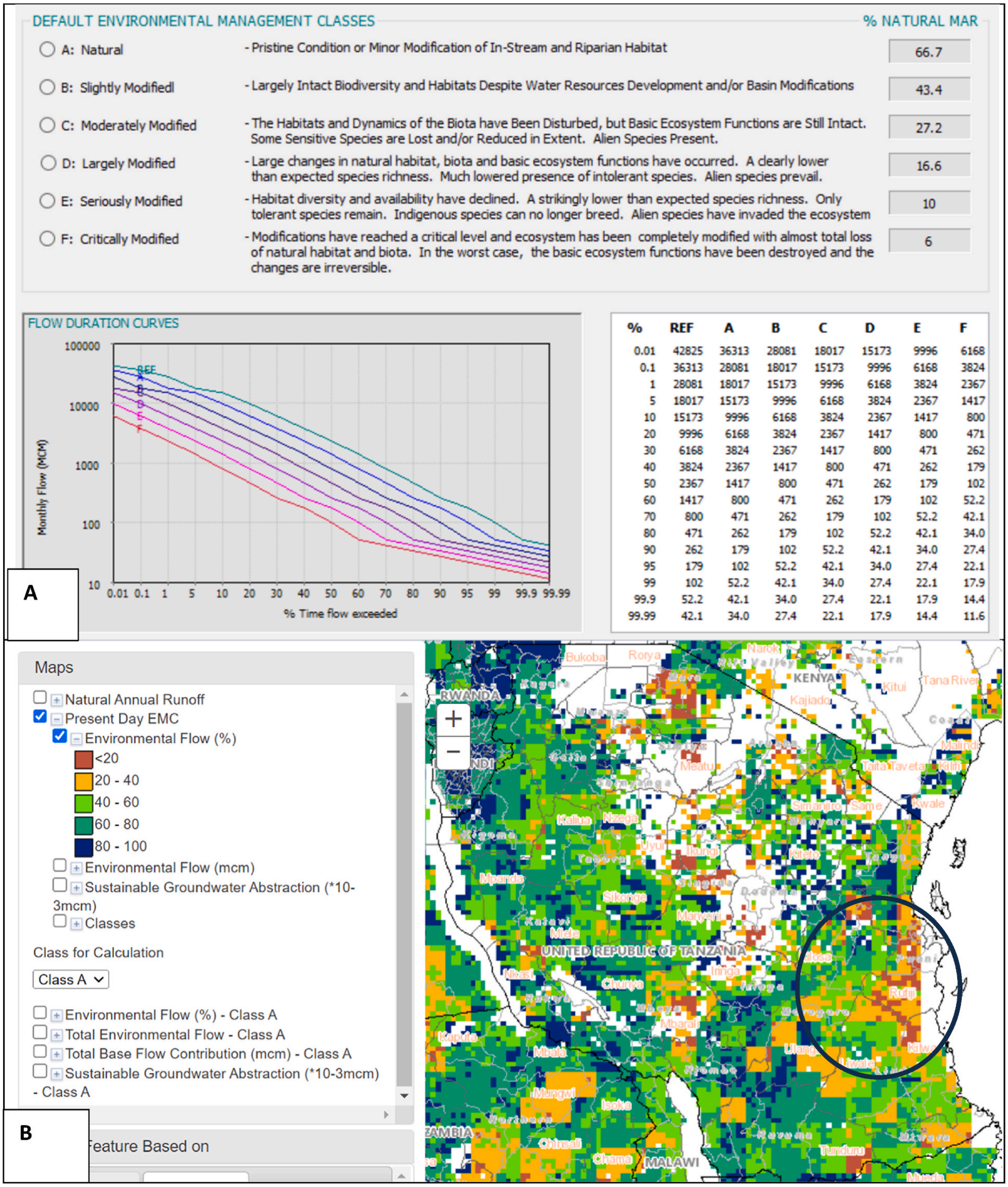


Fig. 11. Environmental management classes and Flow duration curves at Stiegler's Gorge calculated by the GEFC. These data are provided by the Water Systems Analysis Group of the University of New Hampshire, USA - http://www.wsag.unh.edu/(A); and the subsequent validation are given by the Global Environmental Flow Information System (B).

as declines in fish stocks, which affect income and food security. Furthermore, changes in water availability and quality can have adverse effects on tourism and ecotourism activities, reducing tourist arrivals and affecting the local economy.

4.4. Economic implications

The Rufiji River's environmental flow is subject to alterations caused by factors like dam construction, water diversion, and climate change, resulting in significant consequences for various sectors. Losses in fisheries and agricultural productivity have economic implications, including reduced food security and increased poverty. Tourism and recreational activities are affected by changes in the river's flow, leading to declining wildlife populations and a decrease in tourist visits. Additionally, conflicts over water allocation may arise due to the disruption of ecosystems and the socioeconomic impacts on human populations. A study by Geressu [56] proposes to compare the energy, agricultural, and environmental conservation trade-offs implied by different extents of development for future systems using a multisector spatial computer-aided design.

4.5. Losses in fisheries and agricultural productivity

The alteration of the Rufiji River's environmental flow has economic consequences, particularly in terms of losses in fisheries and agricultural productivity. This can occur due to factors like dam construction, water diversion, and climate change, which disrupt the river ecosystem and affect aquatic and terrestrial resources. The decline in fisheries has a significant impact, as the Rufiji River plays a crucial role in providing employment and income opportunities through fish production [46]. Changes in the river's flow also affect agricultural productivity, as farmers rely on it for irrigation and crop cultivation. Altered flow patterns lead to water scarcity for irrigation, resulting in reduced crop yields and potential economic losses for farmers. These changes have far-reaching implications, including reduced food security, increased poverty, and economic instability in the region.

4.6. Effects on tourism and recreational activities

The Rufiji River Basin is renowned for its biodiversity richness and stunning landscapes, attracting tourists and nature enthusiasts. Wildlife tourism is a primary economic activity that relies on this abundant and diverse wildlife. Changes in the river's environmental flow disrupt ecosystems and wildlife habitats, leading to a decline in wildlife populations [27]. Altered environmental flow might also affect recreational activities like fishing and boating, impacting local fishermen's income and livelihoods. Maintaining adequate environmental flows is essential for sustainable fisheries and the well-being of local communities. Sustainable management practices are necessary to preserve the Rufiji River ecosystem and ensure the long-term viability of tourism and recreational activities in the region.

4.7. Potential for conflicts over water allocation

Changes in the Rufiji River's environmental flow can trigger conflicts over water allocation. The river supports diverse ecosystems, and alterations in its flow regime can have ecological and socioeconomic implications. Reduced water flow can lead to the degradation of wetlands and the loss of critical habitats for various species. Human populations relying on the river for agriculture, domestic use, and hydropower generation are also affected. Water scarcity due to reduced flow disrupts irrigation schemes, affecting crop yields and livelihoods of farmers potentially leading to conflicts. Conflicts may also arise between different sectors competing for water allocation, such as hydropower projects, and other stakeholders like agricultural communities and environmental conservation groups [46]. It is crucial to consider the consequences of altering the river's flow regime to ensure sustainable water allocation and minimize conflicts.

5. Conclusion

The environmental flow assessment is a popular tool that has been widely adopted to support informed decision-making regarding the sustainable management and utilization of water resources in river systems. This particular scoping study covered several aspects, including geomorphology, ecology, hydrology, climate status and projections, and socioeconomic drivers in the Lower Rufiji River Basin. The study suggests that hydrological and holistic frameworks or approaches are common in Tanzania. Further, there has been evidence from literatures that e-Flow is still evolving, that there has been limit in addressing downstream biophysical and social impacts, and that there is a need for improvement and or utilization of several methods/approaches to compare the findings in these ungauged catchments. It is worth preserving the habitat connectivity of the LRRB by maintaining dynamic environmental flow regimes. Future research should focus on quantifying contribution of base flow, salinity dynamics in the LRRB, especially during the low flows.

Data availability statement

Data included in article and/or referenced in article.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Offoro N. Kimambo: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Winfred Mbungu:** Writing – original draft, Investigation, Formal analysis. **Goodluck D. Massawe:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Amina A. Hamad:** Writing – original draft, Visualization, Investigation. **Elly J. Ligate:** Writing – original draft, Visualization, Validation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Offoro N. Kimambo reports financial support was provided by Sokoine University of Agriculture. Offoro N. Kimambo reports a relationship with Sokoine University of Agriculture that includes: employment. Offoro N. Kimambo has patent NONE pending to NONE. NONE.

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