Hydrologic classification of Tanzanian rivers to support national water resource policy

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Hydrologic classification of Tanzanian rivers to support national water resource policy

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Abstract

Classifying rivers into homogeneous categories based on hydrological and/or environmental attributes supports the implementation of environmental flows to sustain aquatic ecosystems and support the resource needs of society. Hydrological classifications provide decision-makers with a pragmatic number of water management units by grouping individual rivers or river segments expected to exhibit similar biophysical responses to flow alteration. Such classifications are particularly useful across broad geographies and in data-limited contexts, such as in Tanzania, where the legal requirement to implement environmental flows for all major waterbodies remains constrained by scant data. We present a two-level hydrological classification of all Tanzanian basins and the Rufiji River Basin. For the Rufiji River Basin, the largest river basin in the country, we performed an inductive classification based on the availability of long-term time series of daily average discharge. We clustered 28 gauging stations into seven classes according to ecologically relevant hydrological metrics and used boosted classification trees to predict the hydrological class of all 95,909 river segments in the basin based on environmental attributes that influence flow regimes. In the absence of consistent, readily-available gauged flow data, we conducted a deductive classification of all Tanzanian rivers whereby segments were directly grouped by multivariate similarity using the same environmental attributes. This analysis revealed 10 river classes reflecting the diversity of ecohydrological conditions characterizing the 486,681 river segments draining in and out of Tanzania. The new hydrological classifications presented here provide the foundation to guide implementation of management practices within the water policy framework of Tanzania.

KEYWORDS
environmental flow, flow regime, hydrologic classification, reserve, Rufiji River basin, Tanzania, water management, water policy

1 | INTRODUCTION

Fresh water is essential for ecosystem health and underpins the economies and lifeways of human populations around the world (UNESCO, 2020). Human control of river flows is now nearly ubiquitous globally, resulting in only a third of large rivers still remaining free-flowing over their length (Grill et al., 2019). Sources of hydrologic alteration constitute a persistent threat to the biophysical vitality of river systems and are a leading cause of now grave declines in biological diversity and ecosystem function (Tickner et al., 2020). As a result, considerable attention is now focused on designing and implementing the environmental flows (i.e., the magnitude, duration, timing, frequency, and rates of change and quality of freshwater flows) required to sustain the health of aquatic ecosystems and, in turn, support human cultures, economies, livelihoods, and well-being (Anderson et al., 2019).

Hydrological classification—the process of systematically arranging streams, rivers, or catchments into types that are most similar with respect to characteristics of their flow regime—has long played an essential role in ecohydrology by aiding the understanding of geographic, spatial and temporal patterns in flow regimes. More recently, it has emerged as a critical process, and often an early step, in environmental flow assessments (Arthington, 2012; King et al., 2000; Poff et al., 2010; Tharme, 2003). The classification of hydrological regimes serves to reveal the influence of natural and regulated discharge on species, communities and ecosystems, guides monitoring programme design and prioritization of water management practices and informs environmental flow assessments that aim to be broadly generalizable and representative of the diversity of different ecosystems (Olden et al., 2012). This is particularly relevant in countries of the Global South that struggle to navigate trade-offs between meeting societal water demands and supporting functioning ecosystems (UN, 2018). At the same time, these countries often require greater funding to support more robust hydrometric monitoring networks (Ruhi et al., 2018).

Recent decades have witnessed the adoption of the concept of environmental flows in numerous countries in Central and South America, Africa, and Asia (Tharme, 2003), where the requisite legislation, practical experience and capacity are rapidly advancing (Anderson et al., 2011; Harwood et al., 2017; McClain & Anderson, 2015; Poff et al., 2017). Tanzania, for instance, is working towards socially and environmentally sustainable water resources management under a supportive policy and legislative framework (CDM Smith, 2018), alongside ambitious targets for its socioeconomic development (World Bank, 2017). The Tanzania National Water Policy of 2002 (URT, 2002) provides a comprehensive framework for the sustainable development and management of the nation's water resources to meet both human and ecosystem needs for all priority waterbodies. Further, the Water Resources Management Act No. 11 of 2009 (URT, 2009) establishes the legal priorities for water allocation in Tanzania, with the water required for basic human needs receiving the highest priority, followed by water for the environment as the second right by law. Together these are referred to as the "reserve" and are to be defined and managed for prior to allocation of water for other purposes. Quantified environmental flows as part of the reserve are recognized as an important management tool for the maintenance of the ecological character of the country's wetlands, including those of international importance under multilateral agreements, and of its internationally transboundary river and lake systems (Dickens, 2011; CDM Smith, 2018; URT, 2016; Wilson et al., 2017).

Environmental flow assessments have been conducted across Tanzania (Dickens, 2011; Kabogo et al., 2017; Kashaigili et al., 2007; McClain et al., 2013; O'Keeffe et al., 2019; Seeteram et al., 2019; CDM Smith, 2016, 2018), but there remains no coherent national or basin-level classification to represent the diverse ecohydrological characteristics of the streams and rivers that comprise the country. There is also no consistent approach either in use, or in the currently proposed guidance documents, for classifying river segments according to shared hydrogeomorphic similarities (Kaaya, 2015). To support national policy and basin management objectives, we developed a river classification for Tanzania. This systematic river classification is designed to be applied at national and basin scales in Tanzania. The goals were to help guide the rapid, precautionary setting of environmental flows (known as the reserve) for entire river systems, and to facilitate efforts to prioritize the siting of new flow gauging station networks to support integrated water monitoring. Our approach was designed to be sufficiently flexible procedurally to support implementation of the Tanzania Water Resources Management Act (URT, 2018) and to be amenable to future revision as further data become available.

Our specific objectives were to develop hydrologic classifications at two distinct spatial extents. First, we performed an inductive classification of the rivers of the Rufiji River Basin according to ecologically relevant hydrologic metrics estimated from long-term discharge records from river gauging stations. The Rufiji River Basin is Tanzania's largest river basin and is considered a model basin for the application of a range of water resource management tools due to past and projected future socioecological development and climate change (e.g., Chilagane et al., 2020; England, 2019; Kihwele et al., 2018; Näschen et al., 2019). The resulting hydrologic classes were mapped and characterized according to their defining hydrologic conditions. Second, we conducted a deductive classification of all river segments across Tanzania according to multivariate similarities in physiography, climate, hydrology, land-use, and population density attributes that influence flow regimes (rather than based on hydrological records, due to inconsistent national gauge coverage). River classes were predicted for close to half a million river segments. The new hydrological classifications we present provide the foundation to guide the design, site selection, and environmental flow assessments necessary to quantify the reserve, which under national policy are to be in place and operationalized for every single water body of water management interest within the country by 2035 (CDM Smith, 2018).

2 | METHODS

2.1 | Study system

As the largest country in East Africa, Tanzania possesses a tremendous variety of inland freshwater systems of exceptional biodiversity and wildlife conservation value (Seeteram et al., 2019). The nation's freshwaters are also recognized as providing essential and valuable ecosystem services that support the social and economic development and resilience of Tanzanian society. Tanzanian rivers have a total exploitable hydropower potential of approximately 4700 MW, but to-date only approximately 560 MW have been developed through a combination of mini, small and large hydropower (Mdee et al., 2018). There are currently six large hydropower plants in operation, and a number of other projects have been considered over the past two decades, including in the Ruhudji, Mnyera, and Mpanga river basins (Adebayo et al., 2013). What will be the fourth largest in Africa, the Julius Nyerere Hydropower Project (2115 MW) at Stiegler's gorge, began construction in July 2019.

Of the nine major river and lake basins of Tanzania that comprise the Tanzanian Water Resource Management System, the Rufiji River Basin is the largest, occupying approximately 20% of the national territory and supplying some 25% of the country's renewable water resources. Basin altitude ranges from sea level at the Indian Ocean to more than 2960 m above sea level in the highlands of the Kipengere ranges and Poroto Mountains (Wilson et al., 2017). Estimated mean annual precipitation over the entire Rufiji Basin is 1070 mm year^{-1}. Rains begin in October–November due to the southward movement of the Intertropical Convergence Zone, a period known as the short rains, followed by the northward movement of this same zone in March to April where rainfall intensifies, generating the main wet season of the long rains.

2.2 | Overview of hydrologic classification

We developed hydrologic classifications at two distinct spatial extents: (1) an inductive classification of the rivers of the Rufiji River Basin and (2) a deductive classification of all Tanzanian rivers nationwide (Figure 1). The choice of classification approach was dictated by the availability of streamflow (river discharge) data (Olden et al., 2012). The strength of any inductive classification is defined largely by the quantity (number and spatial distribution of stream gauging stations) and quality (period of record, accuracy) of stream discharge data. For this reason, considerable effort was spent to gather, process, and analyse data from the hydrometric network of river gauging stations for the Rufiji River Basin in collaboration with local experts. At the national scale, deficiencies in gauging data, either with respect to the absence or scattered distribution of river gauging stations or constraints in ready access to quality-controlled data from basin authorities within the study timeline, necessitated a deductive classification approach for Tanzanian rivers. Classification protocol co-design, data acquisition and quality control were informed by a structured series of in-depth consultations with hydrologists, hydrogeologists, water resource engineers, hydraulic modellers, freshwater ecologists, social scientists, and practitioners active in water resource management in Tanzania, including within the Directorate of Water Resources, Ministry of Water (MoW), the Rufiji Basin Water Board (RBWB) and representatives of several other Basin Water Boards, and local universities.

2.3 | River hydrography and environmental attributes

A digital river network was generated using global drainage direction maps (HydroSHEDS; Lehner et al., 2008) derived from elevation data at 3 arc-second (~90 m at the equator) resolution. The smallest sized streams delineated through this process drained a catchment area of ~1 km^2 (118 pixels), resulting in 95,909 river

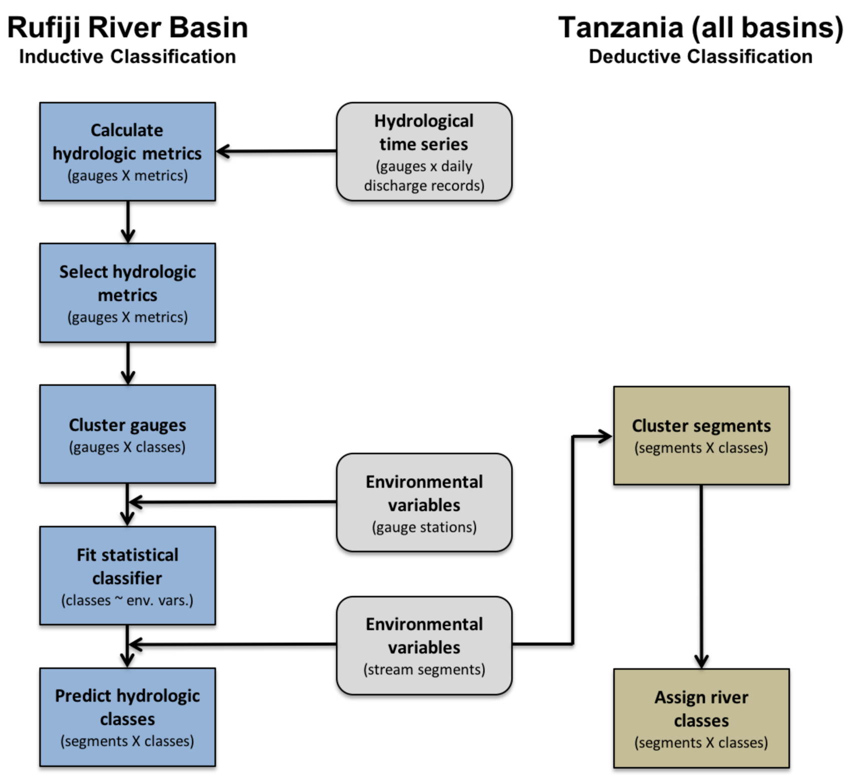

FIGURE 1 Schematic diagram summarizing the steps involved in defining the inductive classification for the Rufiji River basin (left side, blue) and the deductive classification for Tanzania (right side, brown). The light grey boxes (center) represent data inputs. Environmental variables for river segments were used both for predicting hydrologic classes to all river segments of the Rufiji River basin and as a starting point to create the national deductive classification. The output of each step is shown in parenthesis in small font where "X" refers to a table. For instance, "gauges X metrics" refers to a table where each row corresponds to a river gauge and each column a hydrologic metric such that each cell contains the value of a given hydrologic metric for a given river gauging station. "Classes ~ env.Vars" refers to the modeled statistical relationship between hydrologic classes and environmental variables

segments within the Rufiji River Basin and 486,681 river segments within the borders of Tanzania. Next, over 200 variables describing physiography, climate, hydrology, land-use, and population density in the Rufiji River Basin (and all of Tanzania, when possible) were calculated in a Geographic Information System (GIS) using a variety of global and national sources of data. All GIS analyses were performed using the Esri ArcPy library in Python and are freely available for reuse (see Data Availability Statement). A subset of

TABLE 1 Environmental variables used to predict hydrologic classes for Rufiji River basin (inductive classification) and develop river classifications for Tanzania (deductive classification)

Variable	Scale	Unit	Source
Physiography			
Elevation[a]	Reach	m	SRTM3[h]
Elevation	Catchment	m	SRTM3
Slope[b]	Catchment	°	SRTM3
Drainage area	Catchment	km^2	Network[i]
Climate and catchment hydrology			
Water occurrence[c]	Subcatchment	%	Pekel et al. (2016)[j]
Water seasonality[d]	Subcatchment	Months	Pekel et al. (2016)
Lake index[e]	Catchment	%	HydroLAKES[k]
Mean temperature of warmest quarter[f]	Catchment	°C	Worldclim v2[l]
Mean temperature of coldest quarter	Catchment	°C	Worldclim v2
Annual precipitation	Catchment	Mm	Worldclim v2
Precipitation seasonality[g]	Catchment	Mm	Worldclim v2
Precipitation of wettest quarter	Catchment	Mm	Worldclim v2
Precipitation of driest quarter	Catchment	Mm	Worldclim v2
Annual potential evapotranspiration (PET)	Catchment	$kJ/m^2/day$	CGIAR-CSI global-PET[m]
Land cover and land use			
Vegetation cover	Catchment	%	Sentinel 2[n]
Agricultural cover	Catchment	%	Sentinel 2
Built up areas (urban cover)	Catchment	%	Sentinel 2
Geology			
Depth to bedrock	Catchment	Cm	SoilGrid[o]
Subsoil permeability	Catchment	—	GLHYMPS[p]
Subsoil porosity	Catchment	—	GLHYMPS

[a]Computed after removal of erroneous values (>6000 m) from 1″ SRTMGL1 v3.0 digital elevation model and subsequent infilling by Euclidean allocation and bilinear resampling for alignment with HydroSHEDS 3″ drainage direction data.
[b]Computed using Horn's method with latitudinal corrections for the distortion in the XY spacing of geographic coordinates by approximating the geodesic distance between cell centres with online tools (from http://www.jennessent.com/arcgis/surface_area.html).
[c]Lake index reflects the degree to which the flow regime of a given river segment might be influenced by a body of water upstream. For a given river segment, it is computed as the ratio between the segment's drainage area at its downstream end (catchment size) and the drainage area at the outlet of the nearest upstream lake or reservoir.
[d]Water occurrence shows where surface water occurred between 1984 and 2015 and provides information concerning overall water dynamics by capturing both intra-annual and inter-annual variability and changes (see Pekel Cottam, Gorelick, & Belward, 2016, for additional information).
[e]Water seasonality reflected as the number of months that water was present for a single year (2014–2015).
[f]All raster data in numeric format with spatial resolutions coarser than 3″ were resampled by bilinear interpolation or cubic convolution.
[g]Precipitation seasonality is the standard deviation of monthly precipitations divided by annual precipitation (i.e., coefficient of variation).
[h]NASA Shuttle Radar Topography Mission Global 1 arc second V003 (Farr et al., 2007) (https://earthexplorer.usgs.gov/).
[i]Produced as part of this study based on HydroSHEDS 3 arc second drainage direction maps (Lehner et al., 2008) (http://www.hydrosheds.org/page/overview).
[j](https://global-surface-water.appspot.com/).
[k]Includes all global lakes and reservoirs >10 ha (Messager, Lehner, Grill, Nedeva, & Schmitt, 2016) (http://www.hydrosheds.org/page/hydrolakes).
[l]Fick and Hijmans (2017) (http://worldclim.org/version2).
[m]Zomer Trabucco, Bossio, & Verchot. (2008) (http://www.cgiar-csi.org/data/global-aridity-and-pet-database).
[n]Drusch et al. (2012) (http://2016africalandcover20m.esrin.esa.int/download.php).
[o]Hengl et al. (2017) (ftp://ftp.soilgrids.org/data/recent/).
[p]GLobal HYdrogeology MaPS (Gleeson et al., 2014) (http://spatial.cuahsi.org/gleesont01/).

20 variables, describing conditions at a variety of spatial (segment, sub-catchment, catchment) and temporal (years, decades) scales (Table 1), were selected based on expert knowledge of direct associations with river hydrology and a review of the literature (Olden et al., 2012). Segments are defined as a cartographic unit represented by the digital line segments between neighbouring river confluences as delineated in the GIS, sub-catchments are the areas that exclusively drain to a given segment (excluding areas that drain to upstream segments), and catchments include the entire upstream area that drains to a given segment.

2.4 | Inductive hydrologic classification for the Rufiji River basin

2.4.1 | Assembling hydrologic data

An extensive quality control process was implemented in collaboration with scientists and water managers of the RBWB (detailed in Supporting Information A). This resulted in the identification of an initial set of 37 river gauging stations in the Rufiji River Basin where it was possible to acquire time series of measured average daily discharge. Station coverage was strong in the various tributaries of the Great Ruaha River sub-basin, but noticeably more limited on the mainstem Rufiji and in the Kizigo River catchment (Figure 2). Gauging stations were also generally well-represented in the Kilombero River sub-basin, particularly the northern tributaries, although few stations existed on the mainstem and lower Kihansi River. There is a dearth of hydrologic data for the Luwegu and Lower Rufiji sub-basins, which have only two and three gauging stations, respectively. Moreover, these stations have been poorly maintained, due to inaccessibility, highly variable floodplain conditions and/or resource constraints, with limited monitoring conducted and data of uncertain quality. For this reason, the hydrologic classification of these areas was not interpreted. The river gauging stations collectively represent the environmental variability expressed across all stream segments in the Great Ruaha and Kilombero sub-basins of the Rufiji River Basin (Figure A1). Gauged rivers span the gradient of catchment sizes,

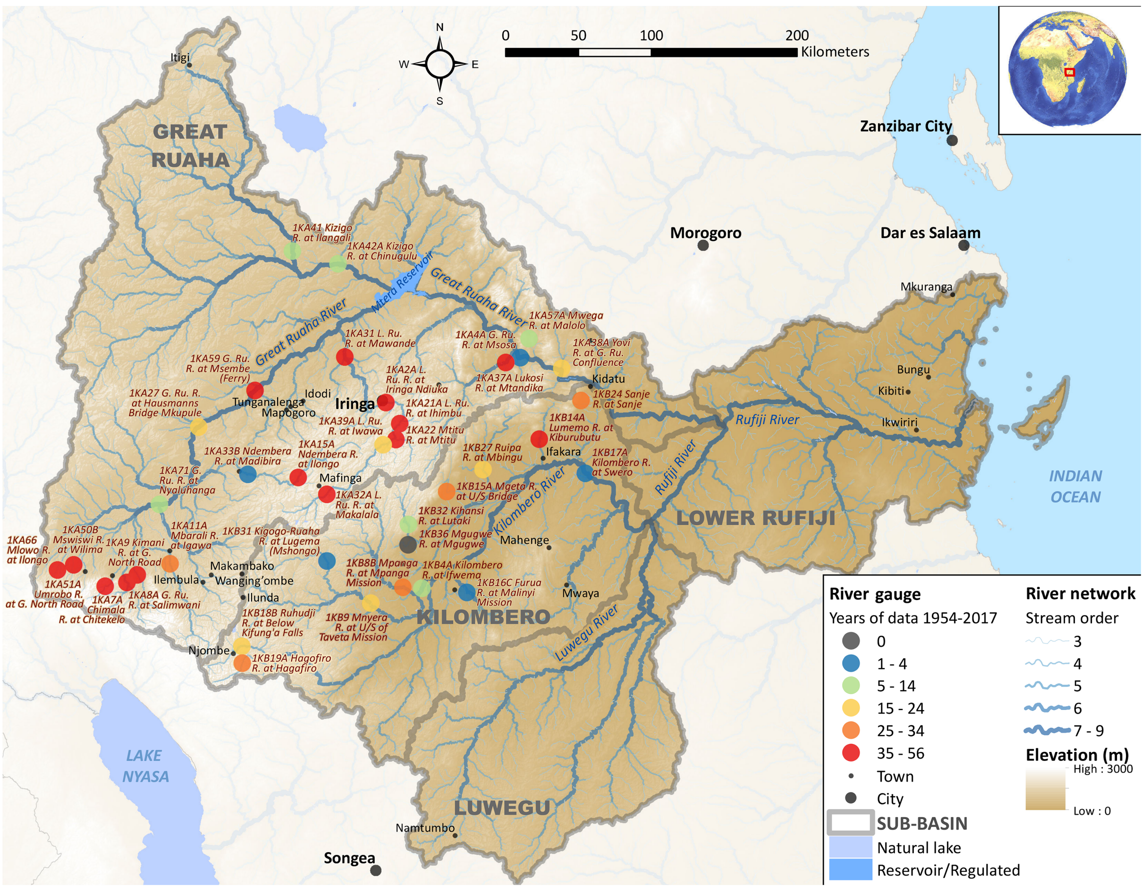

FIGURE 2 Map of the locations and length of river discharge record (number of years of data) for 37 river gauges (colored circles) in the Rufiji River basin, Tanzania. Only hydrologic years (October 1 to September 30 of the following year) for which less than 10% (37 days) of daily river discharge data are missing were used in the computation of the number of years of data. The river gauge on the Mgugwe River at Mgugwe (1KB36) therefore does not have any valid year of data despite having recorded data from December 2015 to July 2016. Abbreviations in the river gauge names refer to R., river; G., great; L., little; and Ru., Ruaha. For example, G. Ru. R. at Msembe is shorthand for great Ruaha River at Msembe

elevations, climates (precipitation), lithologies, land uses (forested, urban), human population densities, and flow regulation by reservoirs.

2.4.2 | Gauge selection for hydrological classification

A series of diagnostic analyses was conducted to explore the suitability of river gauge hydrologic data for inclusion in the hydrologic classification. These steps are summarized below but described in greater detail in Supporting Information B. All hydrologic data manipulation and analyses were performed in a reproducible format in the free, open-source R statistical environment (R Core Team, 2013) and are freely available for reuse (see Data Availability Statement). First, time series analyses of average daily discharges for all river gauges were conducted, including an analysis of data quality, temporal trends, and potential regime shifts (change points) in discharge patterns. Second, we evaluated the length and degree of temporal overlap across gauges records (Figure 3). On average, stream gauges contained 40 years of daily discharge data (without considering within-year data gaps), ranging from a minimum of 2 years (Mgugwe River at Mgugwe, 1 KB36—gauge ID native to Rufiji Basin Water Board data management system) to a maximum of 64 years (Kimani River at Great North Road, 1KA9). Many river gauges contained gaps where discharge data were missing. The average percentage of missing data per year across all gauges was 15%, ranging from 2% to 59%. Third, the completeness and timing of hydrologic records across the station network were assessed. Trade-offs in selecting which gauging stations to use existed between maximizing the number versus the required minimum record length and acceptable level of missing data (Figure B1). We adopted 15 years of daily discharge data as a suitable minimum record length based on the sensitivity analysis for hydrologic classifications of Kennard et al. (2010).

To ensure adequate data quality in the hydrologic classification, we first required all gauging stations to have at least 15 years of daily discharge data during the period 1954 to 2017, excluding years (for this gauge selection and subsequent analysis) with more than 10% of missing records (i.e., 37 days). We made exceptions for three gauges: two on the Kizigo River (1KA41, 6 years; 1KA42A, 7 years) that were deemed important to include, because they were the only representatives of this large, seasonal river basin, and one on the Kihansi River at Lutaki (1KB32) with 14 years of data. This resulted in 28 of the original 37 stream gauging stations to be retained.

The selected gauges contained an average of 32 years of discharge data (as of early 2018). Gauges are located on river segments whose catchments are free of reservoirs, have not experienced significant forest loss (<25%, period 2000 to 2016), and are characterized by limited urban land cover (<2%; Figure A1). Missing daily discharge data records (for periods of no more than 37 days) were replaced with interpolated values for each gauge time series using the "na.interp" function from the "forecast" package in the R statistical environment (Hyndman et al., 2017; Hyndman & Khandakar, 2007). After a Box-Cox transformation, this function first fits a Seasonal and Trend decomposition using Loess (STL), then interpolates the seasonally adjusted discharge time series, and lastly re-seasonalizes the value. Following this initial computation, the

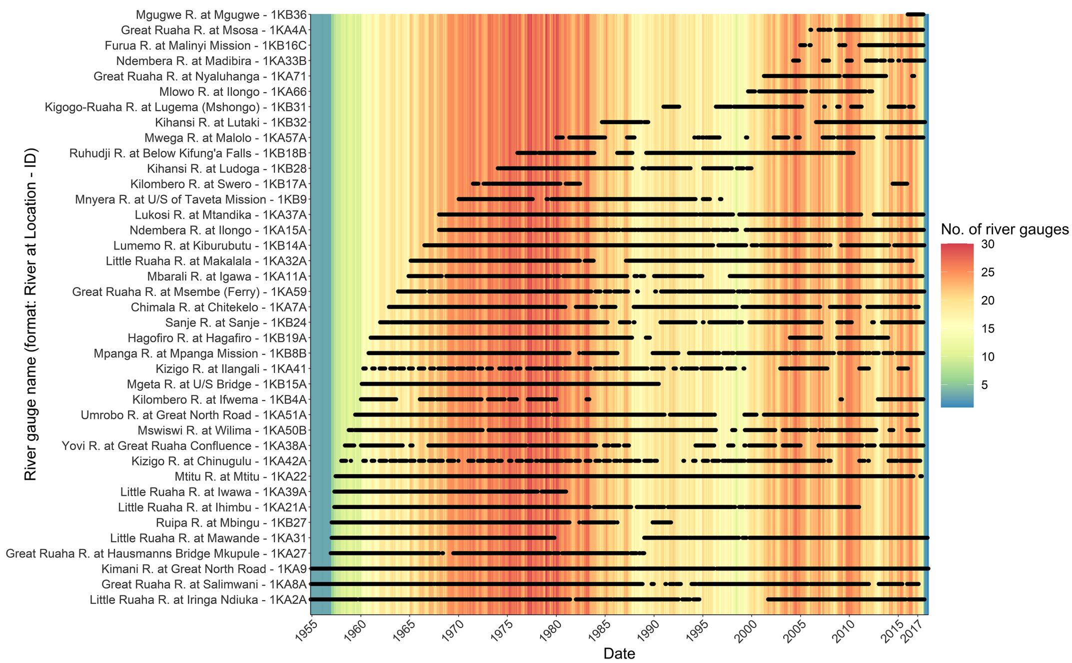

FIGURE 3 Summary of available discharge data. Summary of available discharge data for the 37 initial river gauging stations of the Rufiji Basin (individual horizontal black lines) and the degree of data overlap in terms of the total number of river gauges with discharge data for each day from 1954 to 2017 (vertical colored shading). This dataset omits all daily discharge records that were deleted during the quality control procedure but does not include interpolated values

time series were examined, and anomalous values generated through the seasonal interpolation were deleted and replaced by simple linear interpolation. For the two stream gauges on the Kizigo mainstem (sites 1KA41 and 1KA42A), the data imputation method based on STL produced poor quality discharge estimates. Therefore, several other interpolation methods were tested to address these periods of "missing" data and an autoregressive moving-average model was fitted to each time series with Fourier series and daily observed precipitation data from a pluviometric station as external regressors (Supporting Information B). Hydrographs for all 28 stream gauging stations deemed suitable, including deleted records and periods corrected for missing data, are provided in Supporting Information C.

2.4.3 | Calculation of hydrologic metrics

Inductive river classifications generally rely on hydrologic metrics that characterize statistical properties of the hydrologic regime of rivers based on multi-year discharge time series. Numerous hydrologic metrics can be used to describe ecologically relevant components of the hydrologic regime (Olden & Poff, 2003), and there are many considerations when deciding on the hydrologic metrics to be included in a classification (Archfield et al., 2014; Olden et al., 2012). To reduce subjectivity in selecting our flow regime descriptors, we calculated 171 hydrologic metrics using the "EflowStats" package in the R statistical environment (Mills & Blodgett, 2017). Metrics accounted for all of the five main criteria used to characterize flow regime variability within and between years, namely magnitude, timing, frequency, duration, and rate of change of flow, and spanned the high flow and low flow components of hydrographs. Table D1 contains a full description of the hydrologic metrics selected.

To avoid a predominance of river size alone in determining river classes, hydrologic metrics related to the magnitude of the flow regime were normalized based on drainage area; this is commonly done in hydrological classifications (Olden et al., 2012). Normalization focused on area, rather than mean annual discharge, to retain differences in discharge that are due to hydrometeorological and catchment differences among rivers of similar drainage area. Summary statistics across the entire river gauging network are presented in Figure E1. Statistical redundancy among the hydrologic metrics was minimized by selecting a final set of 119 hydrologic metrics. The extent of multicollinearity among hydrologic metrics, as evaluated by examining Pearson correlations between all metrics, was generally low. The majority (i.e., >80%) of between-metric comparisons had absolute correlation coefficients <0.5, and ~7% of comparisons had absolute correlation coefficients >0.8.

2.4.4 | Hydrological classification

We used an agglomerative hierarchical clustering with Ward's minimum-variance algorithm to reveal evidence for distinct hydrologic classes. Specifically, the 28 stream gauging stations were clustered according to multivariate similarity based on the 119 hydrologic metrics (the pairwise Gower's distance calculated among gauges with z-score standardized hydrologic metrics). Ward's algorithm is considered a space-conserving approach (i.e., it is not biased with respect to artificially forcing the formation of clusters) and has been shown to maximize clustering performance as defined by the cophenetic correlation coefficient (i.e., the linear correlation between the distances among the gauges, according to dendrogram branches, and the original pairwise Gower's distances among gauges). In addition, this algorithm eliminates group size dependencies on the clustering results, an important feature given the small number of gauges included in the analysis. The scree plot of the resultant dendrogram and support of different cluster solutions were assessed according to the gap statistic and in consultation with hydrologists familiar with the study region. The gap statistic compares the total within intra-cluster variation for different values of k (# of clusters) with their expected values under null reference distribution of the data (Tibshirani et al., 2001) and was calculated using the "cluster" package in the R statistical environment.

2.4.5 | Prediction of hydrologic classes across the Rufiji River basin

We used a classify-then-predict approach that involved first classifying river segments with gauging stations based on the hydrologic metrics (see above) and then predicting the class of all other segments of the Rufiji River Basin based on environmental variables and a statistical model (Snelder & Booker, 2013). Adaptive boosting according to classification trees was used to predict hydrologic class as a function of physiological, hydro-climatological, land cover and land use, and geological attributes (Table 1) for 95,909 river segments. Classification trees are particularly powerful for ecological analyses because they allow the modelling of nonlinear relationships among mixed variable types, they are invariant to monotonic transformations of the independent data that are often required prior to using traditional methods, and they facilitate the examination of intercorrelated variables in the final model (Olden et al., 2008). Adaptive boosting algorithms are a model-averaging or ensemble-based approach in which multiple classification tree models are built using random subsets of the data, leading to improved predictive performance by weighting tree outputs according to their accuracy (Elith et al., 2008). Here, the boosted regression tree was implemented using the "adabag" package in the R statistical environment based on 2000 iterations and using bootstrapping, after square-root or log-transformation and z-score standardization of the environmental variables. Variable importance is based on the number of times a variable is selected for splitting, weighted by the squared improvement to the model as a result of each split, and averaged over all trees (Elith et al., 2008).

2.5 | Deductive hydrologic classification for all basins of Tanzania

2.5.1 | Environmental data

The national deductive hydrologic classification relied on the same digital river network and the same 20 environmental variables as the inductive classification used for the Rufiji River Basin (Table 1). To encompass the range of environmental attributes that characterize the entire drainage network of Tanzania, all transboundary river segments that eventually contribute flow to areas within the national borders were included in the analysis. The Tanzania-wide classification is deductive in the sense that streams and rivers are classified according to similarities in environmental attributes that influence flow regimes rather than an inductive classification based on hydrologic metrics, as in the case of the Rufiji River Basin. Therefore, the classes in this classification are referred to as *river classes* rather than *hydrologic classes*.

2.5.2 | River classification

Agglomerative hierarchical clustering with Ward's minimum-variance algorithm was also used to reveal evidence of river classes for Tanzanian basins. The clustering algorithm grouped all 486,681 river segments according to multivariate similarities based on the 20 environmental attributes. Euclidean distance on z-score standardized environmental variables was used in the cluster analysis. The computational requirements of Ward's algorithm are substantial, therefore we implemented this analysis using the "fastcluster" package in the R statistical environment (Müllner, 2017). The scree plot of the resultant dendrogram and support of different cluster solutions were assessed in consultation with local hydrologists, but computer memory limitations precluded calculation of the gap statistic.

3 | RESULTS

3.1 | Inductive hydrologic classification for the Rufiji River basin

Seven distinct hydrologic classes were identified for the Rufiji River Basin according to similarities based on their suite of hydrologic metrics (Figure 4, scree plot presented in Figure F1). There was evidence for a strong degree of clustering in the dendrogram (agglomerative coefficient = 0.88), support for seven clusters (gap statistic = 0.71, SE = 0.01), and pairwise inter-gauge distances reflected in the branching architecture were significantly correlated to pairwise Gower's distances according to the hydrologic metrics (cophenetic correlation coefficient = 0.43, $P = 0.038$). The boosted classification trees highlighted the primary importance of average channel slope (19% of overall information gain), catchment area (14%), segment and catchment elevation (11% and 8%, respectively), occurrence of water (9%), annual precipitation (8%), and subsoil porosity (6%) in predicting hydrologic class membership (Figure 5).

Each hydrologic class is discussed below with respect to differences in geography, stream size (low stream order indicating small streams and large stream order indicating large rivers), annual hydrographs, and mean (and variation in) hydrologic metric values (values of all 171 hydrologic metrics for each hydrologic class are presented in Table G1). For the purposes of presentation, hydrologic classes are also given names that best reflect the distinctive flow characteristics of their gauge membership, although we recognize that intra-class

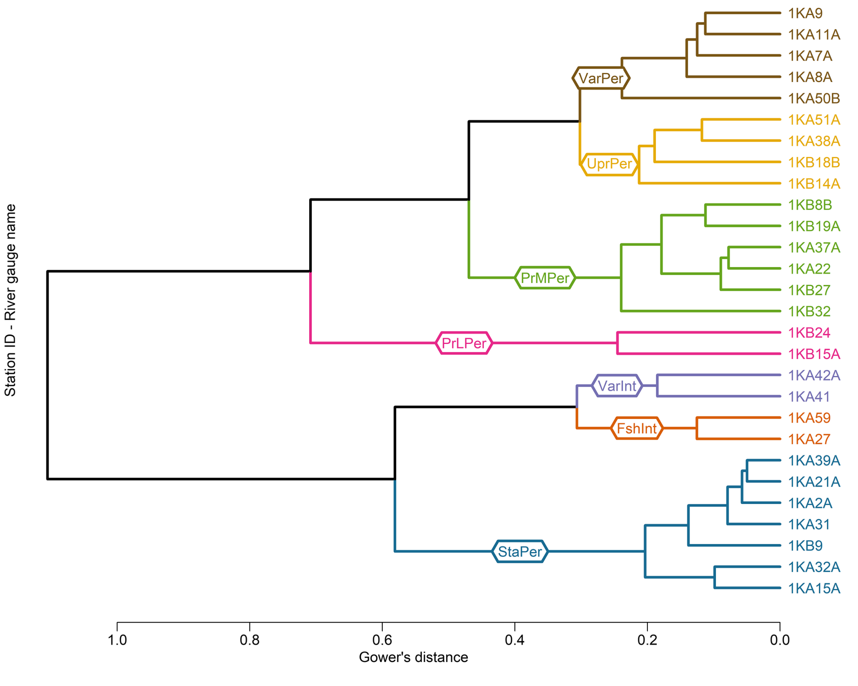

FIGURE 4 Dendrogram depicting the seven hydrologic classes resulting from the hierarchical clustering of the 28 river gauging stations in the Rufiji River basin according to the 119 selected hydrologic metrics. The horizontal axis of the dendrogram represents the multivariate distance between river gauges and between clusters according to the metrics. Classes include stable perennial (StaPer), flashy intermittent (FshInt), variable intermittent (VarInt), predictable low-order perennial (PrLPer), predictable mid-order perennial (PrMPer), unpredictable perennial (UprPer), and variable perennial (VarPer)

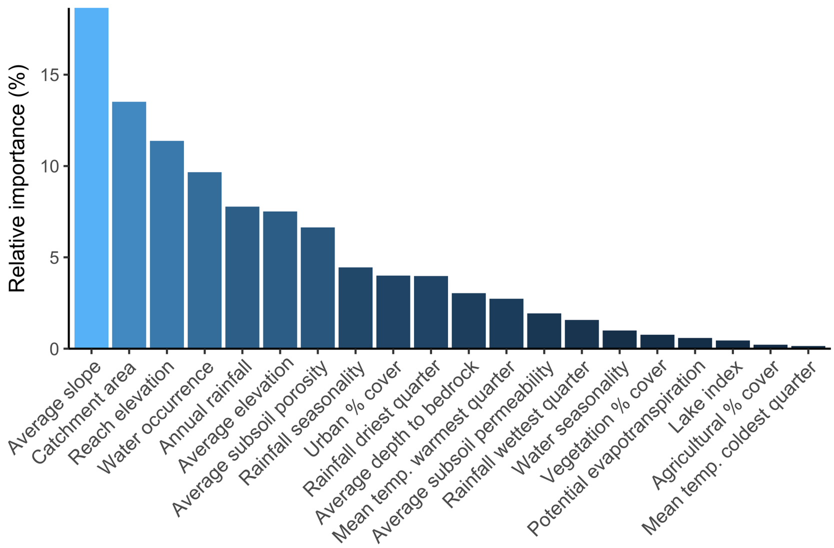

FIGURE 5 Relative importance of environmental variables in predicting the hydrologic class of each river segment in the Rufiji River basin from the boosted regression tree. Variable importance is based on the number of times a variable is selected for splitting a tree, weighted by the improvement to the model as a result of each split, and averaged over all trees. Temp, temperature

flow variability exists and thus class names are not perfectly descriptive.

Stable Perennial (StaPer) hydrologic class is represented by river gauging stations on the medium-sized (mid-order) Little Ruaha and Ndembera rivers, as well as a single station in the Mnyera River (Kilombero River Basin) (Figure 6a,b). Defining hydrological characteristics include: low variability in daily flow (MA3), low monthly average flows (MA24–35), low flood pulse count (FL2) and timing of annual low flow (TL2); low annual maximum flow (DH1–2) and low variability in maximum monthly (MH13) and annual flows (MH18); and subtle flow rise rates (RA1), fall rates (RA3), and daily flow changes (RA6) (Figures 7 and 8).

Flashy Intermittent (FshInt) hydrologic class is represented by two river gauging stations in the large (high-order) mainstream Great Ruaha River (Figure 6a,b). Defining hydrological characteristics include: high magnitude of average (MA13–18), minimum (ML2–7), and maximum flows (MH2–7) during the end of the hot dry season and extending into the long rain season (February–July); high range in daily flow magnitude (MA6) and variability in annual flows (MA42–44); low flood frequency (FH1, 5, 6, 8–11, DH22); long duration of flood pulses (DH15, 17–24); and high number of zero-flow days (DL18) (Figures 7 and 8).

Variable Intermittent (VarInt) hydrologic class is represented by two river gauging stations on the temporary Kizigo River (Figure 6a,b). Defining hydrological characteristics include: high magnitude of average (MA22–23) flows during the short rain season (November to December); high variability in daily (MA3, MA40, 42–45), minimum (DL6–10) and maximum flows (DH6–10); low magnitude and high variability in baseflow (ML17–21) and very high number of zero-flow days and months (DL18, 20); high frequency (FH7), count (FH3, 4), and duration of large floods (DH14); and early and high interannual variability in dates of minimum (TL1–2) and maximum (TH1–2) daily flows (Figures 7 and 8). Caution is recommended when interpreting the specific values of the hydrologic metrics for these stations and the geographic extent of this class, given that it was necessary to interpolate a large portion of their discharge record.

Predictable Low-order Perennial (PrLPer) hydrologic class is represented by two river gauges on small low-order tributaries of the Kilombero River sub-basin (Figure 6a,b). Defining hydrological characteristics include: lower magnitude of average (MA12–14), minimum (ML1–3), and maximum flows (MH1–3) during the hot period of the dry season (January to March); low variability in minimum low flows (DL6–10); and higher frequencies of short duration of both high flows and floods (FH5–11, DH17, 20–21) (Figures 7 and 8).

Predictable Mid-order Perennial (PrMPer) hydrologic class is represented by river gauges on mid-order tributaries of the Kilombero, Great Ruaha, and Little Ruaha sub-basins (Figure 6a,b). Defining hydrological characteristics include: high magnitude of average (MA19–21) and minimum (ML8–10) flows during the late, cool dry period (August to October); high minimum flows over daily, weekly, and monthly time periods (DL1–5); elevated baseflow conditions (ML19) and high flow constancy (TA1) and predictability (TA2); low variability in daily range of flows (MA5, 7) and in minimum (DL6–10) and maximum flows over daily, weekly, and monthly periods (DH6–10); low variability in rise and fall rates (RA2,4); and low high flow discharge (MH15–17) and peak flows (MH24–27) (Figures 7 and 8).

Unpredictable Perennial (UprPer) hydrologic class is represented by river gauges on low-order tributaries of the Kilombero and Great Ruaha sub-basins (Figure 6a,b). Defining hydrological characteristics include: low magnitude of average (MA12–14), minimum (ML1–3), and maximum flows (MH1–3) during the hot period of the dry season (January to March); higher variability in low flow and high pulse duration (DL17, DH16); low flood interval (DH22); and low predictability of average (TA2) and high flows (TH3) (Figures 7 and 8).

Variable Perennial (VarPer) hydrologic class is represented by high elevation headwater streams of the Great Ruaha River sub-basin (Figure 6a,b). Defining hydrological characteristics include: low mean

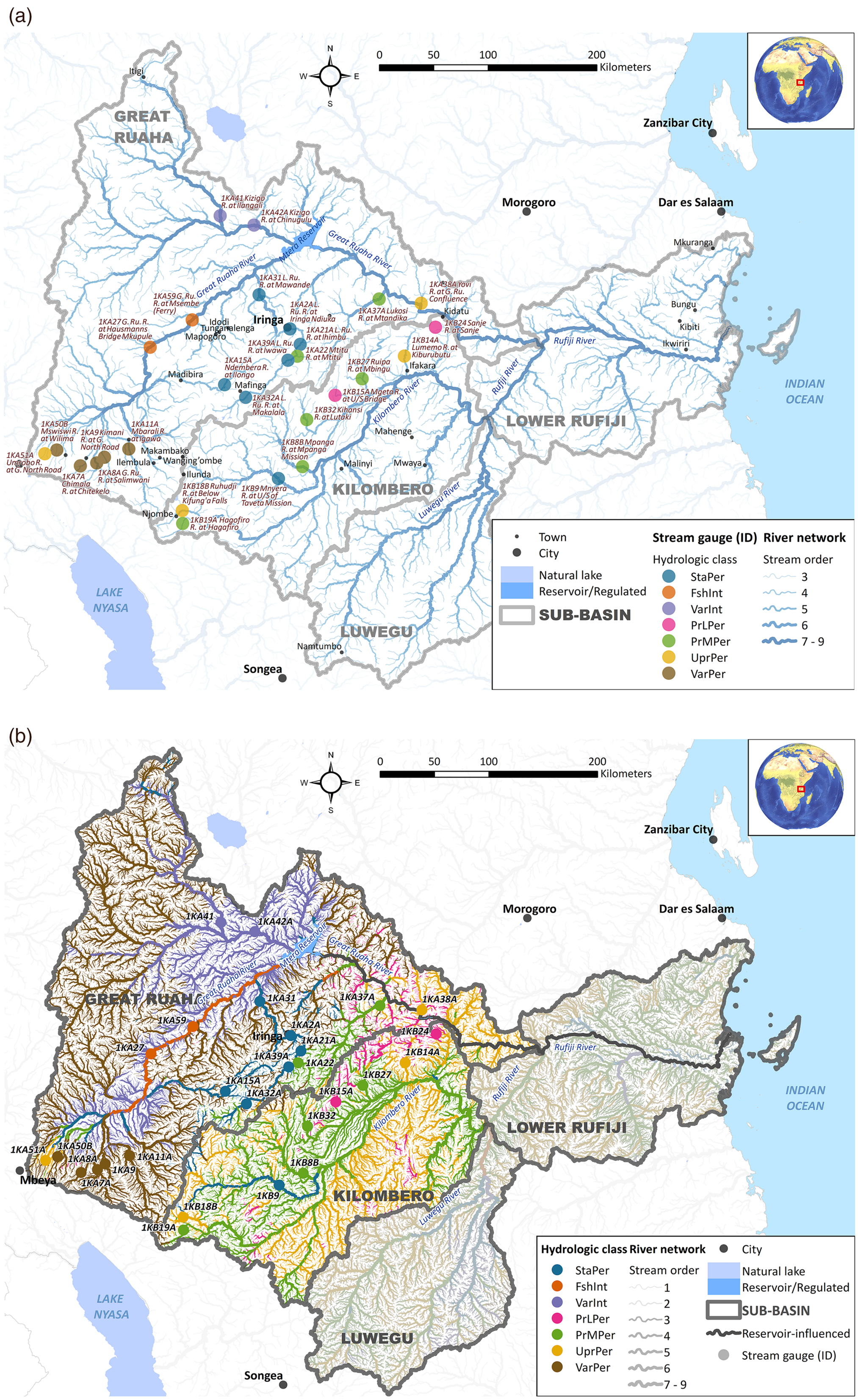

FIGURE 6 (a) Map of the seven hydrologic classes for the 28 river gauging stations in the Rufiji River basin. (b) Predicted hydrologic classes of all river segments in the Rufiji River basin according to the boosted classification tree model. Streams of the lower Rufiji and Luwegu Rivers are purposely omitted because no gauging records from these catchments were available. The class colors correspond to those presented in Figure 4. Classes include stable perennial (StaPer), flashy intermittent (FshInt), variable intermittent (VarInt), predictable low-order perennial (PrLPer), predictable mid-order perennial (PrMPer), unpredictable perennial (UprPer), and variable perennial (VarPer)

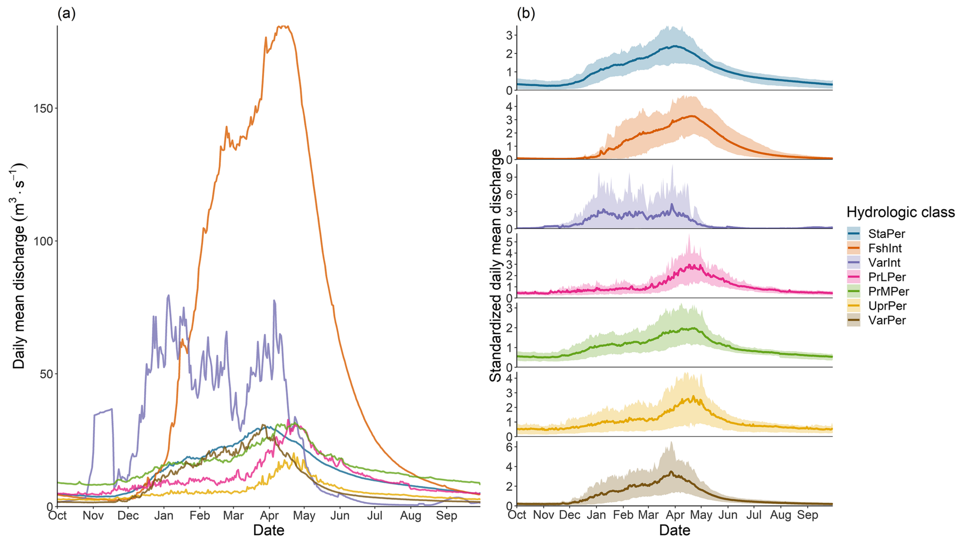

FIGURE 7 Annual hydrographs for each of the seven hydrologic classes in the Rufiji River basin. (a) Daily mean discharge (y axis) was calculated by averaging, for each calendar day (x axis), the daily discharge over all years of data across all gauges for each class. (b) Standardized daily mean discharge was calculated by first dividing each daily discharge record by the mean annual flow that year and then averaging these normalized values across all years and gauges for each class. Solid lines represent average daily values, while the shading represents the 10th (lower limit of shading) and 90th (upper limit of shading) percentiles of the daily discharge for that day of the year across all stream gauges and years of data. All daily values were weighted equally such that gauges influence the shape of the hydrographs proportionally to the number of years of data in their record. Classes include stable perennial (StaPer), flashy intermittent (FshInt), variable intermittent (VarInt), predictable low-order perennial (PrLPer), predictable mid-order perennial (PrMPer), unpredictable perennial (UprPer), and variable perennial (VarPer)

daily flow (MA1) and low average (MA20–22), minimum (ML9–11) maximum (MH8–11) monthly flows during the late cool dry and short rain seasons; elevated high flow discharge (MH15–17), volume (MH21–23), and peak (MH25–27); high variability in daily flows (MA4, 9–11); and low seasonal predictability of flooding (TA3) and predictability (TA2) (Figures 7 and 8).

Upon the request of multiple local experts during the consultation process, two additional classifications were conducted: (1) including stream gauges with discharge time series of 5 years or fewer years of record to increase sample size, and (2) comparing two periods (1958 to 1983 vs. 1991 to 2016) reflecting a regional shift in climatic conditions. In both cases, there was high similarity between the classification presented here and the classification based on the alternative datasets (see Supporting Information H).

3.2 | Deductive hydrologic classification for Tanzania

The final river classification for 486,681 river segments of Tanzania according to similarities in their environmental attributes is presented in Figure 9. Although a moderate change in the scree plot (Figure I1) indicated that 12 classes would be acceptable, the river segments pertaining to the 12th river class were located almost entirely outside of Tanzania (i.e., in transboundary basins), and two classes were merged into one as they were both related to lake influences. Therefore, the final classification of Tanzanian rivers contained 10 classes. Each river class is discussed with respect to geography (Figure 9) and defining environmental attributes (Figure 10 and Table J1). Class names are exclusively based on environmental attributes rather than on river hydrology, given that no hydrologic data were used in developing this classification (e.g., here the terms *Dry* and *Wet* refer to precipitation levels and are thus only indirectly related to flow regime).

Urban (Urban) river class is represented by stream segments within or downstream of urban areas. These rivers are likely to be most affected by water withdrawals for industrial and domestic uses, urban effluents that might affect instream water quality, and structural changes to riparian and instream physical habitat (e.g., channelization and removal of bank vegetation). Defining environmental characteristics include: high percentage of built-up areas (impervious urban land cover) in their sub-catchment; and a low percentage of vegetation cover in their wider catchment.

Lake-Influenced (LkInf) river class includes all drainage segments within the river network where the flow regime is influenced by the upstream occurrence of a lake or wetland outlet. The flow regimes of the rivers in this class are thus likely to exhibit more stable intra-annual flows. For river segments draining from a regulated lake (i.e., an existing natural lake the outlet of which has a dam for water level management, potentially altering lake levels, e.g., Lake Victoria) or reservoir, their hydrology is likely to be governed by the operational rules of the flow-regulating structure. Defining environmental characteristics include: high lake index, implying that a large portion of the river segment's watershed drains into a nearby lake or reservoir upstream; and low depth to bedrock and high subsoil porosity.

Coastal-Wet (CoaWt) river class is represented by a band of lowland rivers along the Indian Ocean coast that stretches from 50 km

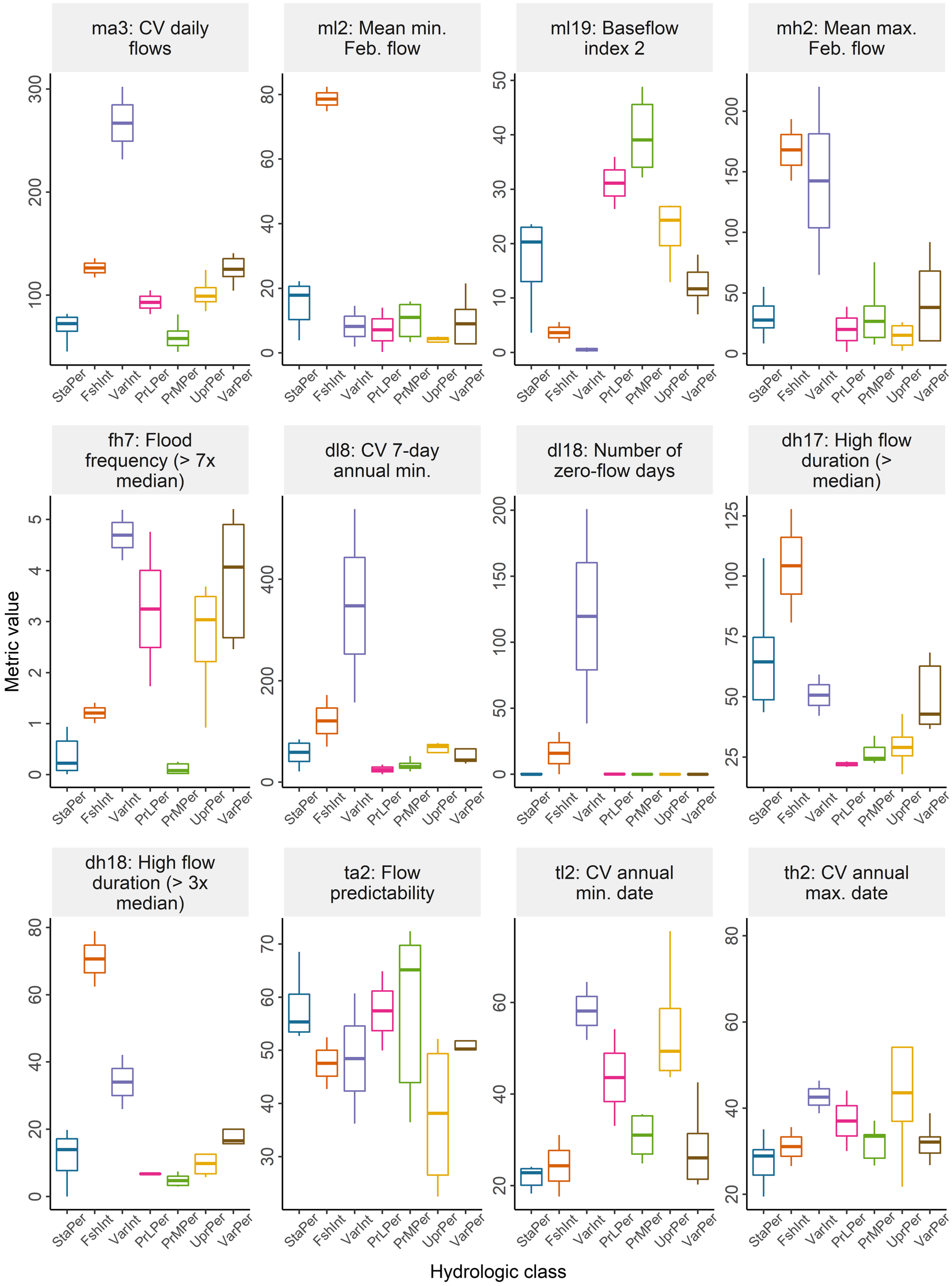

FIGURE 8 Boxplot comparison of selected hydrologic metrics between hydrologic classes of the Rufiji River basin. Boxplots represent median (horizontal line), 25th and 75th percentiles (boxes' lower and upper sides, respectively), 1.5*interquartile range (vertical lines/whiskers), and outliers (points) of each hydrologic metric across all 28 river gauges. See Supporting Information D for an explanation of the hydrologic metrics and Table G1 for summary statistics for the 171 hydrologic metrics according to each hydrologic class of the Rufiji River basin. Classes include: Stable perennial (StaPer), flashy intermittent (FshInt), variable intermittent (VarInt), predictable low-order perennial (PrLPer), predictable mid-order perennial (PrMPer), unpredictable perennial (UprPer), and variable perennial (VarPer). CV, coefficient of variation; min, minumum; max, maximum

inland, along most the coast, to over 200 km away from the ocean in the Wami-Ruvu River Basin and Lower Rufiji Sub-basin. This river class also encompasses most of the oceanic island drainages (e.g., Zanzibar Archipelago), except for the streams surrounding the city of Zanzibar, which are classified as Urban. Defining environmental characteristics include: lowest elevation and highest temperature during the hot season; moderate precipitation with low seasonality (relatively high precipitation levels even during the dry season); high subsoil permeability; and high percentage of vegetation and low percentage of agricultural land cover.

Low-elevation Wet Seasonal (LWtSe) river class is characterized by low- and medium-order tributaries in the eastern part of the Rufiji River Basin (all sub-basins aside from the Great Ruaha) and in the Ruvuma River Basin. With respect to its environmental attributes and geography, this river class mainly represents an intermediate class along a gradient from Moderate-elevation Wet Seasonal rivers (see below) to Coastal-Wet rivers—despite its high degree of precipitation seasonality. Defining environmental characteristics include: low elevation; moderate to high precipitation with highest seasonality (very high and very low precipitation levels in the wet and dry season, respectively); low subsoil permeability; and high vegetation cover and low agricultural cover.

Moderate-elevation Wet Seasonal (MWtSe) river class is exclusively represented by drainages throughout the southeastern portion of the country. It characterizes rivers of all stream orders in the Kilombero, Luwegu, Upper Ruvuma, and Southern Lake Nyasa basins. Closer to the coast, a few small order tributaries belong to this class. By contrast, this class predominates in the Lower Rufiji River and mainstem

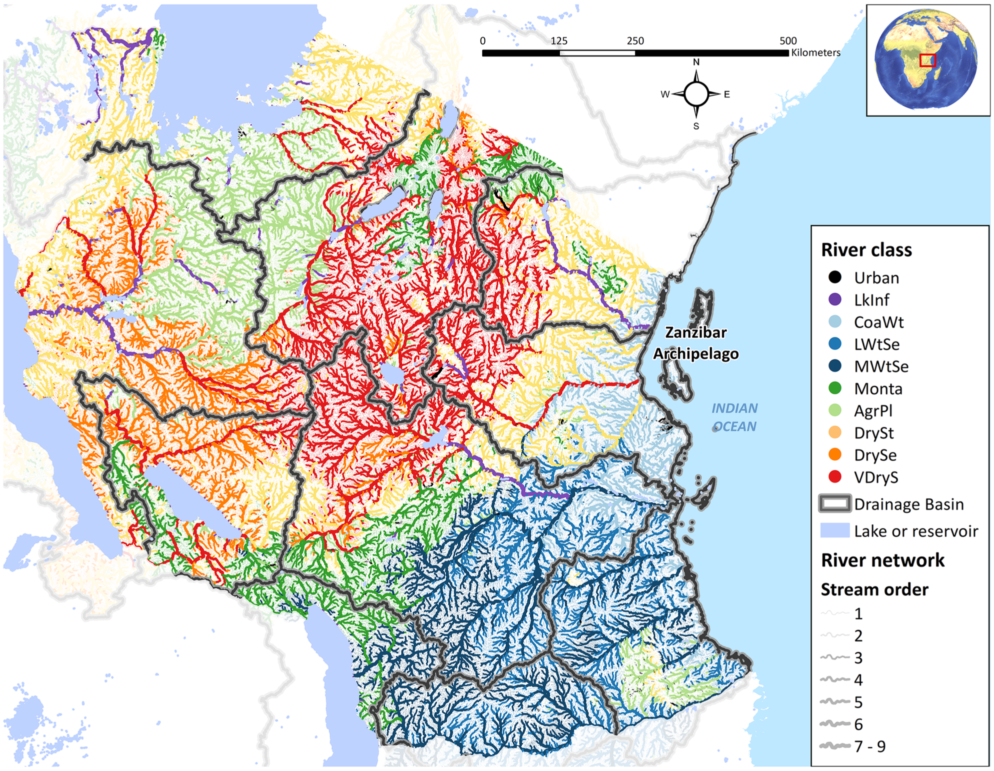

FIGURE 9 Predicted river classes of all river segments in Tanzania according to the deductive classification. Streams of first and second order are displayed with 50% transparency for visualization clarity. Classes include urban (urban), Lake-influenced (LkInf), CoastalWet(CoaWt), Lowelevation wet seasonal (LWtSe), moderate-elevation wet seasonal (MWtSe), montane (Monta), Agricultural Plains (AgrPl), dry stable (DrySt), dry seasonal (DrySe), and very dry seasonal (VDryS)

Ruvuma River as well as high order (larger) rivers along the southern coast river catchments. Defining environmental characteristics include: moderate elevation; highest precipitation levels with high seasonality (highest and very low precipitation levels in the wet and dry seasons, respectively) and low potential evapotranspiration; low subsoil permeability; and high vegetation cover and low agricultural land cover.

Montane (Monta) river class is characterized by streams draining high elevation and high slope catchments. It is consequently found in pockets throughout the country, including a large swath along the southwestern border of the country between Lake Nyasa and Lake Rukwa, extending east along the drainage divide between the Kilombero and Great Ruaha River Sub-basins of the Rufiji. Examples of smaller areas characterized by this river class comprise the region that includes Arusha and Kilimanjaro, as well as the Usambara Mountains in the Pangani River Basin. Defining environmental characteristics include: highest elevation and catchment slope, lowest temperature; variable precipitation amount and seasonality and low potential evapotranspiration; and low (variable) vegetation cover and high (variable) agricultural land cover.

Agricultural Plains (AgrPl) river class is most present in the north-central portion of Tanzania covering a large area from the southern coast of Lake Victoria to the central Tabora region and east until Lake Eyasi. Various other more isolated pockets of this river class exist, including in the headwaters of the Great Ruaha River, on the southern flank of Mount Kilimanjaro, and in the area surrounding the city of Masasi. Defining environmental characteristics include: moderate elevation with lowest catchment slope (aside from lake drainage segments); moderate to low precipitation with moderate seasonality (moderate to low and low precipitation levels in wet and dry season, respectively), and high potential evapotranspiration; highest depth to bedrock; and low (variable) vegetation cover and highest (variable) agricultural land cover.

Dry Stable (DrySt) river class is found in every major Tanzanian river basin, with dense concentrations in the central parts of the Pangani and Wami-Ruvu basins, as well as along the eastern and western shores of lakes Victoria and Tanganyika. Defining environmental characteristics include: moderate elevation and slope; moderate to low (variable) precipitation with low (variable) seasonality; lowest subsoil porosity; and high vegetation cover and low agricultural land cover.

Dry Seasonal (DrySe) river class is almost entirely contained within the Lake Tanganyika and Lake Rukwa basins, but stream segments in this class are also found in small pockets throughout the central and northern part of the country. Defining environmental characteristics include: moderate to low precipitation with high seasonality; low depth to bedrock; and highest vegetation cover and lowest agricultural land cover.

Very Dry Seasonal (VDryS) river class covers the largest contiguous area in the centre of Tanzania, straddling the boundaries of seven major river basins. It encompasses most of the Internal Drainage Basin (Lake Eyasi, Lake Manyara, and Lake Sulunga), the entire catchment of the Kizigo River and Mtera Reservoir, as well as the mainstem of the Great Ruaha River. Because of its prominence in the headwaters of several large catchments, multiple high order rivers are part of this river class and flow across regions that are typical of other river classes (e.g., Wami River and Rungwa River). Defining environmental characteristics include: lowest annual precipitation with high

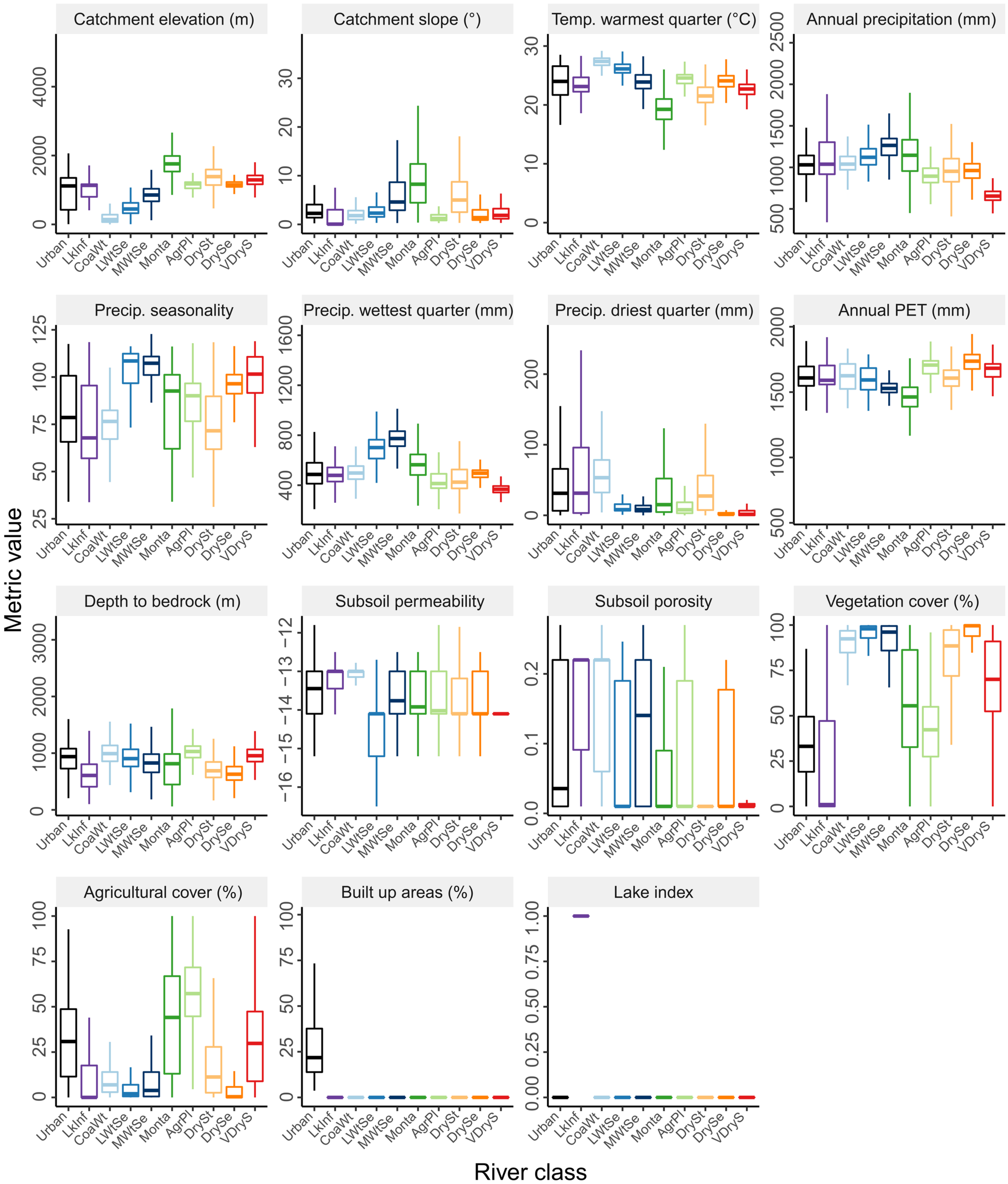

FIGURE 10 Boxplot comparison of selected environmental variables between deductive river classes of Tanzania. Boxplots represent median (horizontal line), 25th and 75th percentiles (boxes' lower and upper sides, respectively), 1.5*interquartile range (vertical lines/whiskers), and outliers (points) of each environmental variable across all 486,681 river segments draining into Tanzania. See Table 1 for a description of the environmental variables. Classes include urban (urban), Lake-influenced (LkInf), coastal-wet(CoaWt), low-elevation wet seasonal (LWtSe), moderate-elevation wet seasonal (MWtSe), montane (Monta), Agricultural Plains (AgrPl), dry stable (DrySt), dry seasonal (DrySe) and very dry seasonal (VDryS). PET, potential evapotranspiration; Precip, precipitation; Temp, temperature

precipitation seasonality and potential evapotranspiration; low subsoil porosity and permeability; and lower vegetated and higher agricultural land cover.

4 | DISCUSSION

Hydrologic classifications provide an important foundational element for designing and implementing practical water management actions. Our study revealed seven distinct hydrologic classes in the Rufiji River Basin that capture the varying magnitude, frequency and timing of key facets of the flow regime. Rivers ranged from small to large, perennial to intermittent (temporary), from stable to flashy, from predictable to unpredictable, with timing of flow characteristics that vary across the wet and dry seasons. However, some aspects of the flow regimes were only weakly represented because of patchy and inadequate spatial coverage of river gauges (discussed more below). Our analyses revealed that climatic and topographic factors (i.e., channel slope, catchment area, elevation, annual total precipitation) were strong predictors of hydrologic class, supporting the view that spatial variation in hydrology is determined by interactions among these factors at multiple spatial and temporal scales.

The deductive classification of Tanzanian rivers revealed 10 river classes that reflect a diversity of ecohydrological conditions as driven by varying magnitude and seasonality in precipitation and air temperature, land use and land cover (vegetation, agriculture, urban), proximity to lakes/reservoirs, pedology (depth to bedrock, soil permeability), and watershed context (elevation, slope). An important result of our study was that the geographical distribution of both hydrologic classes of the Rufiji River Basin and river classes of Tanzania were non-contiguously distributed in space. This was particularly pronounced for Stable Perennial (StaPer), Predictable Low-order Perennial (PrLPer) and Predictable Mid-order Perennial (PrMPer) hydrologic classes in the Rufiji River Basin, and montane (Monta), Agricultural plains class (AgrPl), and Dry stable class (DrySt) river classes of Tanzania. This highlights the care needed when extrapolating flow-regime characteristics from individual gauges to ungauged areas, even those within relatively close proximity (Kennard et al., 2010).

As Tanzania endeavours to navigate trade-offs between meeting societal water needs and supporting functioning ecosystems, there is heightened attention on ongoing water sector reform. National guidance on the procedures for assessing the environmental flow needs of rivers, lakes, and other wetlands exists (URT, 2018), and continues to evolve as the different instruments designed to determine and allocate the reserve are applied in different parts of the country (Kihwele et al., 2018; O'Keeffe et al., 2019). One of the first steps in this process is to classify the water bodies and determine their hydrological status (URT, 2018). Here, we explore the results from both the inductive and deductive classifications, discuss the implications of these results for the national guidelines seeking to ensure sustainable water management in Tanzania, and explore a number of recommendations to assist water resource planners and managers in establishing environmental flow needs both today and in the future.

4.1 | Practical management applications of the hydrological and river classifications

The Rufiji River Basin is targeted for major socioeconomic development over the next two decades as part of the Southern Agricultural Growth Corridor of Tanzania. Increased agricultural productivity, particularly through increased irrigation, and sustainable water resource management is viewed as fundamental to success, where hydrologic classifications provide information on the types and proportional representation of river systems of particular hydrological character that are likely to be affected by human development. In addition to irrigation water demand potentially set to increase by 7 billion cubic metres per year, several new dams and run-of-river hydropower plants are planned to produce 2.4 gigawatts of new hydroelectricity annually (Mdee et al., 2018; CDM Smith, 2016). This includes the planned construction of dams on the Ruhudji, Mnyera and Mpanga Rivers that will threaten Stable Perennial (StaPer) and Predictable Mid-order Perennial hydrologic types, and dam construction on the Upper Kihansi River that will impact Stable Perennial (StaPer) and Variable Perennial (VarPer) hydrologic types in the Rufiji River Basin. Similarly, concentrated hydropower potential in western Tanzania (Mdee et al., 2018) would threaten a number of hydrologic classes, including the Low- (LWtSe) and Moderate-elevation Wet Seasonal (MWtSe) classes and Montane (Monta) class. The controversial decision to begin construction of the Julius Nyerere Hydropower Project (JNHP) at Stiegler's gorge in July 2019, which will represent the fourth largest in Africa and ninth largest in the world, will similarly impact several of Tanzania's most valued rivers (Hamerlynck et al., 2011; Hoag & Öhman, 2008).

The hydrologic classification similarly provides the basis to anticipate the water challenges associated with climate change (Jones et al., 2020). Since 1960, temperatures in Tanzania have been increasing at an average rate of 0.23°C per decade, and annual rainfall has decreased at an average rate of 3.3% per decade (Conway et al., 2017; McSweeney et al., 2010). Projections for the future include changes in the magnitude and timing of rainfall. For example, western parts of the country, southwestern highlands and the eastern parts of Lake Nyasa (Malawi) are projected to experience increased maximum temperatures (+3.5°C) and decreased rainfall (0.5 to 1 mm/day) by middle (2041–2070) and end (2070–2100) centuries according to various emission scenarios (Luhunga et al., 2018), thus potentially altering the hydrological character of Moderate-elevation Wet Seasonal class (MWtSe) and Montane (Monta) classes. Parts of the northeastern highlands are likely to feature increased minimum temperatures in the range of 4.5°C to 4.8°C and increased rainfall over this region and coastal regions are projected to increase under RCP8.5 emission scenario, potentially creating shifts in the ecohydrological character or proportional representation of Dry Stable (DrySt), Dry Seasonal (DrySe) and Very Dry Seasonal (VDryS) classes.

Hydrologic classifications can play a foundational role in Tanzanian regulatory procedures for sustainable water resource planning and management. The hydrologic classification presented here provides an important foundation for the delimitation, characterization, and water resource allocation decisions of the individual surface water bodies for which the reserve (environmental flows) is required to be calculated and gazetted for water infrastructure, permitting, and licensing purposes (URT, 2018). As one example, the development of integrated water resources management and development (IWRMD) plans for individual river basins by the respective basin water boards, as required under the 2009 Water Resources Management Act, is one essential step towards implementing, monitoring, and adaptively managing water for the reserve. Each basin plan must include as one element, among others, a classification of water resources, of which hydrological classification is a vital part. Currently, an IWRMD plan has been adopted in the Rufiji River Basin and is in the final approval stage for the Lake Rukwa Basin, among others.

We also anticipate that in the future, as the ecohydrological, geomorphic, and social knowledge base grows, the hydrologic foundation will allow rapid scaling up of reserve determinations (using established environmental flow methodologies) from individual project sites on river reaches (e.g., single hydropower dams, major irrigation diversions, municipal water offtakes) to whole river systems and classes within a basin or basins. An internationally developed and tested regional environmental flow framework already exists and is in use in several other countries for such a purpose—the Ecological Limits of Hydrologic Alteration (Poff et al., 2010). Presently, no such comprehensive regional scale assessments of environmental water needs have been undertaken in Tanzania, in large part limited by the absence of an appropriately robustly structured and scaled hydrological foundation (in addition to a lack of coupled ecological and river health data). Detailed environmental flow assessments (EFAs) have been made for five of the nine major basins in Tanzania (viz., Wami-Ruvu, Rufiji, Mara, Pangani, and Lake Rukwa (Katuma and Songwe rivers) (CDM Smith, 2018). However, EFAs have not been developed for significant portions of most Tanzanian river basins and, more critically, environmental flows have been implemented—that is, formally adopted through gazetting of the reserve and subsequently applied through water allocations and management—for very few rivers anywhere in the country (CDM Smith, 2018).

Hydrometric networks are critical for allocating resources to support human and ecosystem water needs (often via diversions or flow releases below dams), for forecasting flood and drought risk to societies, and for reducing the systematic over-design of water projects due to missing or unreliable hydrologic data (Ruhi et al., 2018). Our analysis suggests that the current water information system of Tanzania is likely insufficient to support sustainable and resilient water resource management, particularly given the realities of projected socioeconomic development and climate change. In the Rufiji River Basin, for example, we recommend that new stream gauging stations are sited in the mainstem and tributaries of the Lower Rufiji River, Luwegu River, and Kizigo River given the inadequate coverage in these geographies. We recognize that efforts are already underway to strengthen the streamflow monitoring network, with newly installed stations in the Luwegu and Lower Rufiji River Basins in 2018. Additional gauging stations in the mainstem Kilombero River and Luhombero River would also be beneficial. We acknowledge that increasing stream gauging density in Tanzania entails significant challenges related to resources, the size and remoteness of some rivers, and the need for significant participatory involvement (Gomani et al., 2010). Despite these challenges, significant efforts are well underway by the Government of Tanzania to strengthen its understanding of water assets in the country so that projected changes in water supply and demand in the future can be anticipated (Mahoo et al., 2015).

We recommend the creation of the Tanzania Water Information System (TZWIS) to provide an online data depository and information portal for all hydrologic gauging data across the country. TZWIS should be managed by the Ministry of Water through the Centre of Excellence and must be open-access and associated with a standardized set of descriptive metadata for the purposes of identification, structural metadata describing how the data is organized, administrative metadata providing information regarding file types and other technical information, and statistical metadata describing the collection and processing of hydrologic data. As a first step, we recommend that all basin water boards upload annual time series of daily discharge gauging data at the end of each year to TZWIS, although ultimately the availability of real-time data would be optimal. Contribution to, and use of, the TZWIS should be encouraged by freshwater scientists, environmental flow practitioners, and water resource decision-makers. It also should be noted that establishing a centralized water information system affords opportunity for administrative efficiency and associated cost savings, as compared to maintaining nine individually managed systems for each of Tanzania's river basins.

4.2 | Recommended actions to improve the classification results

Monitoring both perennial and temporary (seasonal to intermittent and ephemeral) rivers is critical to meet the challenges of ecologically sustainable freshwater management (Zimmer et al., 2020). The drying-wetting cycle that characterizes temporary rivers uniquely support high biodiversity, biogeochemical processes, and provides important ecosystem services, but is either not or inadequately captured by current stream gauging hydrometric networks (Datry et al., 2018). The Rufiji River Basin is no exception, as only two stream gauging stations are placed on rivers that cease to flow for prolonged periods, in the Kizigo River subbasin. In addition, the hydrological records for these gauges contain gaps as soon as streamflow ceased, making the distinction between no-flow and no-data days impossible, and potentially missing the occurrence of flash floods. This is despite the fact that our classification predicts that temporary waterways comprise a large portion of the Rufiji River Basin and may span over a quarter of Tanzania—Dry Stable (DrySt) and Dry Seasonal (DrySe) classes—and that the naturally seasonal Kizigo River contributes significantly to the water supply volume to Mtera Reservoir. Given that future water diversions and climate change may shift the hydrological character of perennial rivers towards intermittency, as has already occurred for the Great Ruaha River in this basin, it is crucial to develop the region's hydrological monitoring capacity of seasonal, intermittent, and ephemeral rivers.

There is a near-term priority to augment the deductive national river classification presented here with an inductive classification using existing, albeit limited, discharge monitoring data that are available from Basin Water Boards. Here we refrained from conducting a formal comparison of the inductive and deductive classifications (e.g., for assessing the ability of the deductive classification to delineate hydrological groups) as the two groupings were performed at differing extents, therefore likely capturing slightly different scales of processes. Despite concerted efforts to officially acquire the existing hydrological data for the other river basins, only a limited number of station records for a subset of basins was readily available. This particular challenge underscores the vital importance of harmonized basin information systems and standardized, quality-controlled datasets that are consolidated into a single national water information management system. The hydrological classification and physiography, climate, hydrology, and land-use data reported here and made available to all represents a critical first step in this regard.

Future classification efforts should include the delimitation of ecohydrologically, socially, and geomorphologically relevant estuarine and deltaic segments, accounting for available data on the tidal influence and flow-related seasonally varying mix of freshwater and seawater characteristic of the main estuaries of the country. The classification would also benefit from consideration of attributes explicitly reflecting river-floodplain, lake, and other wetland ecotypes. The kinds of geomorphological data and methods suitable for classification represent a significant gap in Tanzania, and we recommend that this disciplinary area be targeted for further development by the research community. A preliminary effort was made to incorporate geomorphic information by including slope and elevation as key environmental variables contributing to a geomorphic classification for the Rufiji River Basin (Supporting Information K). An effort should also be made in the near future to include social data and information in the classifications (e.g., metrics of human well-being, spiritual needs, cultural identity, and sense of place), thereby further expanding their potential for application. This is a new area of development in the science of river classification globally (Anderson et al., 2019) but one which is expected to be particularly relevant for Tanzanian river systems and the diverse communities and livelihoods their natural resource bases support.

5 | CONCLUSION

Water is recognized as playing a pivotal role in the lives of all Tanzanian people, from poverty alleviation, food security, and domestic hygiene security, to the maintenance of healthy and resilient water ecosystems. The hydrological classifications presented here are designed to provide a useful foundation for river conservation planning and ecological management, aiding, for example, in the location of reserve sites and new flow gauging stations and in understanding the potential responses of ecosystems to flow-related water management interventions in Tanzania. The approach is also sufficiently flexible to be amenable to future updates as further data become available nationally or for specific basins. The results of this study can help establish a national water resource information system that acts as an efficient platform for data exchange and source of tools to support basin water boards and ministries achieve more sustainable water management in Tanzania.

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CONFLICT OF INTEREST

None.

DATA AVAILABILITY STATEMENT

All hydrologic data manipulation and analyses were performed in a reproducible format in the free, open-source R statistical environment (R Core Team, 2013) and are freely available for reuse online (at https://github.com/messamat/TZclass). All GIS analyses were performed using the Esri ArcPy library in Python and archived online (at https://github.com/messamat/TZclass_GIS). The outputs of this analysis (gauge classification and GIS layers of the classification) and a snapshot of the programming scripts are also available online (at https://figshare.com/s/2ac31c7687645a51a508).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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