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Environmental flow sustainability in the Lower Limpopo River Basin, Mozambique

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A R T I C L E I N F O

Keywords:
Ecosystem sustainability
Environmental flow requirement
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Water demand
Water scarcity

A B S T R A C T

Study region: This study focuses on the Lower Limpopo River basin (LLRB) in Mozambique, Africa.
Study focus: Maintaining environmental flows necessary for ecosystem sustainability represents a significant challenge to water resource management. In this study the sustainability of LLRB was evaluated by comparing hydrologic availability with ecological and anthropogenic needs. Current river ecological status was scored with a habitat integrity index verified through ground-truthing field surveys and aerial imagery data. Local stakeholder interviews were used to further evaluate the habitat index scores. Deficiencies between water availability and ecological-human requirements were assessed with a water scarcity index.
New Hydrological Insights for the Region: Four environmental flow categories defined as “Excellent”, “Fair”, “Poor”, and “Degraded” coincided to approximately 50 %, 39 %, 27 %, and 14 % of the natural mean annual flow, respectively. Stakeholder interview responses indicated annual water shortages currently occur between August and November and coincide with “Poor” and “Degraded” environmental flow conditions. Water supplies appear to meet consumption needs when calculated on an annual basis with the water scarcity index. However, when calculated monthly, there is not enough to meet human water demand between August and October. This deficit period will likely expand from June to November due to projected increases in future water demands. As the greatest water use in the basin is agricultural irrigation, long-term environmental flows sustainability will likely depend upon effective irrigation management.

1. Introduction

Environmental flows describe the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems (Arthington et al., 2018). The integrity of ecosystems, and the ecological services they provide, in turn supports human cultures, economies, livelihoods and well-being (Rockström et al., 2014). Still, aspects of ecosystems and the flows needed to sustain them are not adequately included in water resources management (Forslund et al., 2009). Sixty-five percent of global river discharge, and the aquatic habitat it supports, is under moderate to high threat (Vörösmarty et al., 2010). The variation of hydrological regimes is vital to sustaining the native biodiversity and aquatic ecosystem integrity. However, this linkage is being negatively affected by flow

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manipulation structures all over the world (Jayasiri et al., 2015; Barbarossa et al., 2020). At the global scale during the 20th century, the combined effect of reservoir operation and irrigation extractions significantly changed the discharge timing and decreased mean annual discharge to oceans by 2.1 % (Biemans et al., 2011). Irrigation demand is expected to increase 6% between 2007 and 2050 (Alexandratos and Bruinsma, 2012). At the same time, projected future global water demand will increase by 55 %, due primarily to growing demand from manufacturing (+400 %), electricity (+140 %), and domestic use (+130 %) (OECD, 2012).

As water withdrawals increase, more river basins will face the challenge of maintaining critical environmental flow levels (Das Gupta, 2008). Globally, the annual Environmental Flow Requirement (EFR) to support “Fair” ecological conditions is between 25 and 46 % of mean annual flow (Pastor et al., 2014). Global water assessments have highlighted regions with current and future water scarcity. However, most studies have neglected EFRs, with only a few attempting to include some ecological aspects (Pastor et al., 2014).

It is expected that by 2025 some countries in the southern region of Africa will face absolute water scarcity while others, including Mozambique, are likely to experience water quality issues in addition to availability problems (Hirji et al., 2002). Addressing the water needs of aquatic, riparian, estuarian, and other associated ecosystems will require strong water conservation efforts in multiple sectors. Tough choices will have to be made to ensure the long-term environmental health of watersheds and the human activities they support (Dyson et al., 2008).

This study evaluated monthly and annual water volume scarcity in the Lower Limpopo River Basin (LLRB) to quantify sustainable balances between ecological integrity and anthropogenic activities. The Limpopo River Basin (LRB) sustains ecosystems that are biologically diverse and provide ecosystem services critical to the human livelihoods among LRB communities. The basin supports an estimated 5200 human settlements of which 49 % lie within Mozambique (UN-HABITAT/UNEP, 2007). In historical times, the Limpopo River was a strong-flowing perennial river but is now regarded as a weakly-flowing perennial river. Flows frequently cease during drought periods and large stretches of the middle and lower reaches of the river may have no surface water present (Ashton et al., 2001). The over-use of water can cause severe water shortages in the lower catchment. Water shortages negatively affect downstream ecosystems and people with a high socio-economic dependence on these ecosystems. FAO-SAFR (2004) reported increases in abstractions are apparent in dry season. As it is not feasible from a socio-economic developmental point of view to maintain or return the natural regime of the river by forcing full reduction of water consumption needs for various uses, it is important to identify a balance between consumption needs for social and economic purposes with the minimum requirements for ecosystem maintenance (Hipolito and Vaz, 2011).

Additionally, because of local data availability, EFR are evaluated from the aspect of water quantity only. Thus, ecological aspects targeting specific species with a specific location in the river ecosystem are not considered in this study.

2. Description of study area

The LRB is a transboundary basin covering a 412,938 km^2 area shared by South Africa (47 %), Botswana (17.7 %), Zimbabwe (16 %) and Mozambique (19.3 %) (FAO-SAFR, 2004). The Limpopo River flows a total distance of 1750 km through the basin with 561 km

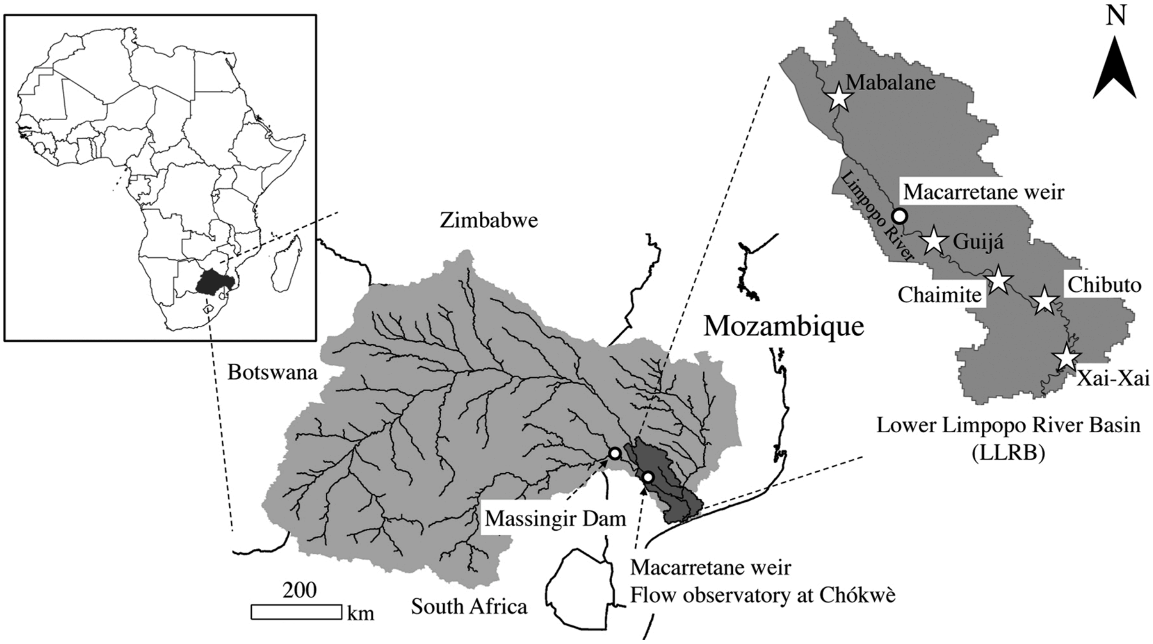

Fig. 1. Outline of the study area. The target watershed is in the downstream of Limpopo river system in Mozambique. Mabalane receives water from the upstream countries, and other cities receives additional water from Massingir dam.

passing through Mozambique until draining into the Indian Ocean (Southern African Research and Documentation Centre, 2003). The LLRB study area encompasses 5618 km^2 in southeastern Mozambique (Fig. 1).

The catchment characteristics of the LRB are diverse, covering different climatic and topographic zones as well as land use types, including protected areas and sensitive ecosystems (African Water Facility, African Development Bank, 2014). In the Mozambique portion of the basin, the climate varies from humid semi-arid to arid. Along the coastal strip, the mean annual rainfall is 800–1000 mm, declining to less than 400 mm in the dry interior bordering Zimbabwe. Rainfall is highly seasonal with 95 % occurring between October and April, often with a mid-season dry spell during critical periods of crop growth (FAO-SAFR, 2004). The temperature and reference evapotranspiration also show variation gradient toward the interior. The average annual temperature in the basin ranges from 23 °C to 26 °C. The largest annual water deficits are observed between September and November. The relative humidity is generally higher than 70 % and may reach even higher values between May and August, except within the drier Pafúri region (Brito et al., 2009). The main channels in the LLRB are the Limpopo River and its tributary the Elephant River (Van der Zaag et al., 2010). The major structures influencing river flow in Mozambique are the Massingir dam, with 2840×10^6 m^3 of capacity, located in the upper portion of the Elephant River, and the Macarretane Weir on the Limpopo River (Boroto and Görgens, 1999). The largest water use in the LLRB is agricultural irrigation (Aurecon AMEI (Pty) Ltd, 2013).

3. Methodology

3.1. Assessment of current river condition

The current condition of the Limpopo River was assessed at fifteen sites from Mabalane to Xai-Xai using a procedure described by Kleynhans (1996) and Kleynhans and Louw (2008). Ground truthing surveys were conducted in the dry season in July 2016. Site visits were selected based on accessibility, land use, topography, soil conditions, irrigation infrastructure, and other water uses influencing water quantity and quality. Geo-referenced photos were taken at all sites (Photo 1) to aid with the evaluation and verification processes. Aerial data including low-level photographs and satellite imagery using Satellite Map - Earth Satellite Image 2016 provided estimates of recent development and activities in the basin. Hydrological and water quality data obtained from Regional Directors of the Southern Waters (Administração Regional das Águas do Sul - ARA Sul) were also used to support ground truthing survey information and aerial imagery.

The method assesses the Present Ecological Status (PES) of the river by calculating a habitat integrity index. To calculate the habitat integrity index, an assessment of modifications at each target site was conducted and scored by using the descriptive classes shown in Table 1. The severity of modification impacts was based on six classes ranging from no impact to critical impact. To score the level of the modifications, a field observation manual developed by Graham and Louw (2009) was used. The manual includes photographic examples of different site modifications and presents scoring procedures, based on site characteristics. Site criteria and scoring weights for incorporating habitat integrity are shown in Table 2. This involves the separate assessment of instream habitat integrity and

Photo 1. Representative sites of PES evaluation and Macarretane weir where river discharge is observed. Six representative photos out of fifteen target sites are shown.

Table 1
Descriptive classes for the assessment of modifications to habitat integrity (Kleynhans, 1996).

Impact class	Description	Score
None	No discernible impact, or the modification is located in such a way that it has no impact on habitat quality, diversity, size and variability.	0
Small	The modification is limited to very few localities and the impact on habitat quality, diversity, size and variability are very small.	1 to 5
Moderate	The modifications are present at a small number of localities and the impact on habitat quality, diversity, size and variability are limited.	6 to 10
Large	The modification is generally present with a clearly detrimental impact on habitat quality, diversity, size and variability. Large areas are, however, not influenced.	11 to 15
Serious	The modification is frequently present and the habitat quality, diversity, size and variability in almost the whole of the defined area are affected. Only small areas are not influenced.	16 to 20
Critical	The modification is present overall with a high intensity. The habitat quality, diversity, size and variability in almost the whole of the defined section are influenced detrimentally.	21 to 25

riparian habitat integrity, according to several key modifiers.

The impact of a criterion in instream and riparian zone was calculated by using Eq. (1).

$$I_{habitat\ integrity} = \frac{S_C}{max_n} \times W_C \tag{1}$$

where $I_{habitat\ integrity}$ is the impact of a criterion on habitat integrity, S_C is the score of the criterion, max_n is maximum score value (Note: limit is 25), W_C is the criterion weight, as percentage.

Following the calculation of habitat integrity, the estimated impacts of all criteria were summed, expressed as a percentage, and subtracted from 100 to arrive at a provisional assessment of habitat integrity for the instream and riparian components, respectively. The final score for the riparian zone and instream components indicates the habitat integrity of the specific segment of the river. The integrity score was subsequently transformed into the ecological category (A to F) according to the EcoStatus classification system in South Africa shown in Table 3.

Following determination and validation of river PES, an evaluation of ecosystem services used by riverine communities near assessed habitat integrity sites was conducted using methodology proposed by Freire (2013). At selected sites, water-related activities conducted by local riparian communities were evaluated as well as the loss of ecosystem services caused by the activity. Effects were quantified through fifteen interviews with individuals and/or groups who were considered to be key river stakeholders having local knowledge of the river. Interview questions are shown in Table 4. The interviewees consisted of individual farmers, farmer's associations, individual fishermen, livestock farmers, local community leaders along / around the river, and water management authorities. Intentional and iterative sampling methods were applied; potential interviewees were identified with the help of staff from the district service of economic activities (Serviços Distritais das Actividades Economicas SDAE) of Chibuto, Mabalane, Guijá and Chonguene. Once resources and their availability to conduct an activity was identified, each activity and/or availability of the natural resources was linked to the indicators of ecosystem services in the river. This was classified based on the concepts of ecosystem functions and services proposed by Costanza (2000), De Groot et al. (2002), and the Millennium Ecosystem Assessment (2005). Using a Likert Scale, responses were qualitatively analyzed. The criteria used accounted for the "perception" of the people interviewed in relation to the environment and natural resource use (Tompkins et al., 2011).

3.2. Environmental flow requirement estimation

Limpopo River discharge data measured at the Chókwè Hydrometric Station was used to estimate the mean monthly flow (MMF) and the mean annual flow (MAF) in the LLRB. The period of record between 1953 and 1971 was selected to represent natural river flow

Table 2
Criteria and weights used for the assessment of instream and riparian zone habitat integrity (Kleynhans, 1996).

Instream criteria	Weight	Riparian zone criteria	Weight
Water abstraction	14	Indigenous vegetation removal	13
Flow modification	13	Exotic vegetation encroachment	12
Bed modification	13	Bank erosion	14
Channel modification	13	Channel modification	12
Water quality	14	Water abstraction	13
Inundation	10	Inundation	11
Exotic macrophytes	9	Flow modification	12
Exotic fauna	8	Water quality	13
Solid waste disposal	6		
Total	100	Total	100

Table 3
Generic ecological categories for EcoStatus components (Kleynhans and Louw., 2008).

Ecological category	Description	Score (% of total)
A	Unmodified, natural	90−100
B	Largely natural with few modifications. A small change in natural habitats and biota may have taken place but the ecosystem functions are essentially unchanged.	80−89
C	Moderately modified. Loss and change of natural habitat and biota have occurred, but the basic ecosystem functions are still predominantly unchanged.	60−79
D	Largely modified. A large loss of natural habitat, biota and basic ecosystem functions has occurred.	40−59
E	Seriously modified. The loss of natural habitat, biota and basic ecosystem functions is extensive.	20−39
F	Critically / Extremely modified. Modifications have reached a critical level and the system has been modified completely with an almost complete loss of natural habitat and biota. In the worst instances the basic ecosystem functions have been destroyed and the changes are irreversible.	0−19

Table 4
Interview questions used to evaluate riverine community perception of ecosystem services.

No.	Interview contents
1	Which activities do you carry out along the river? (What resources do you extract from the river?)
2	How long have you been extracting (benefiting from) the resource? Less than 5 years; 5−10 years; More than 10 years
3	In which period of the year do you carry out the activities / extract the resources?
4	Do you conduct your activities / extract (benefit) the resources normally?
5	When is the critical time of your activities / extract the resources (benefits)?
6	Which component (quantity / quality / vegetation etc.) of the river is necessary to provide the benefits/ to carry on your activities?
7	How do you describe the current condition of the river?
8	Is there any change in the river over the time?
9	Does the change of the river affect your activities / extraction of the resources / benefits you get from the river? Why? (Perception of the loss) • Low (score 1): corresponds to a non-significant reduction in the availability of natural resources or the activity carried out has not been compromised. The analyzed object is considered as present and there is little fluctuation in the availability without provoking concern to the interviewee. The response of the local informant remarks the reduction with expressions that delineate low intensity. • Medium (score 3): corresponds to a non-accentuated reduction in the availability of natural resources or the activity undertaken is compromised. The object analyzed is considered as present, although there is fluctuation in the availability. The response of the local informant remarks a perturbation with expressions which delineate medium intensity. • High (score 5): corresponds to a marked reduction in the availability of natural resources or the activity carried out is highly compromised. The analyzed object is reportedly considered to be scarce. The response of the local informant remarks the reduction with expressions that delineate high intensity.
10	Is the change observed in all years?
11	What is the cause of the change?
12	When did you start observing the change? Less than 5 years; 5−10 years; More than 10 years
13	In which period of the year have you noticed accentuate change of the river?
14	What recommendations would you make to maintain the river in good condition? Why?

conditions because development and water abstraction was considered lower prior to construction of the Massingir Dam which was started in 1972 and finished in 1977.

Based on MMF and MAF values from Pre-Development river flow period, an EFR was calculated for each month (i.e., January through December for the period of record). EFR’s were categorized as “Excellent”, “Fair”, “Poor”, and “Degraded” for different river

Table 5
Categorization of Environmental Flow Requirement (EFR).

Category	Flow	Criteria	EFR
Excellent	Low	MMF < 0.4. MAF	MMF
Excellent	Medium	MMF > 0.4. MAF & 0.4. MMF < 0.4. MAF	0.4. MAF
Excellent	High	0.4. MMF > 0.4. MAF	0.4. MMF
Fair	Low	MMF < 0.3. MAF	MMF
Fair	Medium	MMF > 0.3. MAF & 0.3. MMF < 0.3. MAF	0.3. MAF
Fair	High	0.3. MMF > 0.3. MAF	0.3. MMF
Poor	Low	MMF < 0.2. MAF	MMF
Poor	Medium	MMF > 0.2. MAF & 0.2. MMF < 0.2. MAF	0.2. MAF
Poor	High	0.2. MMF > 0.2. MAF	0.2. MMF
Degraded	Low	MMF < 0.1. MAF	MMF
Degraded	Medium	MMF > 0.1. MAF & 0.1. MMF < 0.1. MAF	0.1. MAF
Degraded	High	0.1. MMF > 0.1. MAF	0.1. MMF

flow conditions (i.e., high, medium, and low flows) following methodology similar to that used by the Grand River Conservation Authority (GRCA, 2017). Table 5 summarizes the ERF categorization methodology used in this study.

After establishing EFR values for MMFs under Pre-Development natural river flow conditions, "Attained EFR" values were calculated for MMFs under Post-Development river flow conditions (i.e., 1983–2015). Whenever the MMF was larger than the EFR value, the largest value of the EFR categories (i.e., Excellent, Fair, Poor, Degraded) was designated the "Attained EFR". Flow data for 2005 was omitted from the analysis because half of MMF values were unavailable for that year.

3.3. Estimation of present and future water demand and use

Present and future water demand and water use were projected for domestic, livestock, and irrigated agriculture sectors. Future projection was set to 2035 based on available data. Data from the Mozambique National Institute of Statistics (Instituto Nacional de Statistical) (National Institute of Statistics, 1997) was used to estimate domestic water demand and water use. A daily water requirement of 50 L per person in rural areas and 150 L per household for urban areas, was based on information from the World Bank and World Health Organization, respectively. The estimation of water demand and use for livestock was based on the livestock data of the administrative posts and localities. A daily water consumption of 35 L, 15 L, and 7 L was estimated for cattle, pig, and sheep and goat, respectively. The future water demand for livestock was estimated using the projection of future livestock number in the basin, made by Administração Regional de Águas do Sul (2017). ArcGIS 10.3.1 was used to calculate the internal population in the target basin from the population and Livestock data of Gaza's districts and posts administrative.

The present and future irrigation water requirement and use were estimated based on registered water user area of the year 2015 and potential planned area. The data were obtained from ARA-Sul. In the case of Mabalane, Administração Regional de Águas do Sul (2017) data representing current operation and future irrigation were used. Climatic data from Chókwè, Chibuto and Xai- Xai from CLIMWAT 2.0 were used to estimate crop water requirement by CROPWAT 8.0. Data from the Direcção Provincial of Agriculture (DPA-Gaza) and SDAEs were used to identify the major crops. Cropping schedules were identified through stakeholder interviews and the Administração Regional de Águas do Sul (2017) study. 60 % of irrigation efficiency was used when water demand for agriculture was estimated. Soil types were identified using the soil map from Aurecon AMEI (Pty) Ltd (2013) and the soil texture content from the report on the Soils of the Limpopo River Basin made by Bangira and Manyevere (2009). Soil characteristics such as hydraulic conductivity and bulk density were defined using the soil texture data and the Soil-Water-Atmosphere-Plant (SWAP) model (Kroes et al., 2017).

3.4. Assessment of water availability considering human and ecosystem requirements

A water scarcity index ($S_{quantity}$) considering water quantity with respect to anthropogenic water use and EFR (Liu et al., 2015) was used to determine if water availability in the LLRB was sufficient to fill both the anthropogenic water demand and environment flows supporting "Fair" habitat conditions. Monthly and annual $S_{quantity}$ were calculated for current (2015) and future (2035) availability. The index uses definitions from the "Water Footprint" concept (Hoekstra and Chapagain, 2007; Hoekstra et al., 2011) including: Blue Water Footprint (BWF) – water that has been sourced from surface or groundwater resources and is either evaporated, incorporated into a product, or taken from one body of water and returned to another, or returned at a different time, Blue Water Resources (BWR) – the total amount blue water of an area or region, and Blue Water Availability (BWA) – total blue water resources minus environmental flow requirement. MAF and MMF rates (m^3/s) were converted to MAF and MMF volumes (m^3) and water-use ratios for irrigation, livestock, and domestic use were estimated at 100 %, 75 %, and 70 %, respectively. $S_{quantity}$ was estimated using the following Eq. (2):

$$S_{quantity} = \frac{BWF}{BWA} = \frac{W \times R}{(BWR - EFR)} \tag{2}$$

Where $S_{quantity}$ is the index of water quantity scarcity; BWF (m^3) is the blue water footprint; BWA (m^3) is the blue water availability, which equals BWR (m^3) minus EFR (m^3); BWR is total blue water resources (m^3); EFR is the environmental flow requirements (m^3); W is the blue water withdrawal (m^3); and R is the water-use ratio describing the proportion of water consumption to total water withdrawal. When $S_{quantity} > 1.0$, the water availability is not enough to meet the demand; at ≤ 1.0, there is sufficient water to meet demand (Liu et al., 2015).

4. Results

4.1. Changes in river discharge

Two periods of record were compared to quantify the changes in Limpopo River flow. Pre-development (i.e., 1953–1971) and post-development (1983–2015) MAFs were determined to be 216.8 m^3/s and 156.8 m^3/s, respectively. After construction of the Massingir Dam, river discharge was reduced an average 60.0 m^3/s. On a monthly basis high flows generally occur between January and March and low flows are observed between August and November. This trend was similar for both pre- and post-development periods. However, in all months, MMF was noticeably lower in the post-development period. The coefficient of variation (CV) shows the degree of flow variation increase after dam construction (Fig. 2).

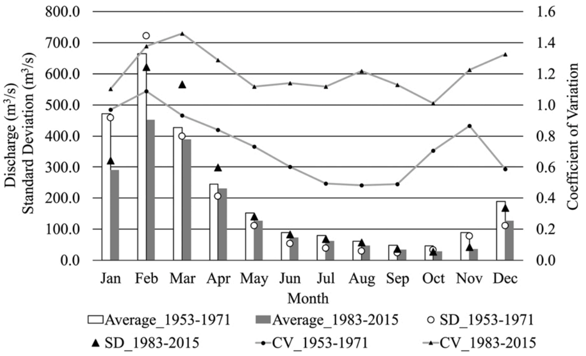

Fig. 2. Comparison of river discharge between 1953-1971 and 1983-2015.

4.2. Present ecological status and perception of ecosystem service loss

The current PES varied from “natural with few modifications” to “moderately modified” (Table 6). PES differences in the assessed sites reflected different activities and activity levels along the river. The major activities identified in the basin included: irrigated agriculture, fishing, gravel extraction and grazing (i.e., livestock production). These activities were one of the indicators of provisioning in ecosystem services, and the fishing activities were also an indicator of habitat function. The effects of farming and grazing were most reported. The assessed Guijá and Xai-Xai sites had low PES relative to other sites due to higher agricultural activity and higher population along the river in these areas.

The loss of ecosystem services varied from high to low among interviewed stakeholders. With exception of Xai-Xai, all sites perceived water shortage as the main reason of loss of ecosystem services affecting their activities. The longest period of water shortage, August to November, was reported in Chibuto. Water abstraction by upstream countries and river regulation by Massingir Dam were reported as significant water shortage factors by many stakeholders. Some considered shortages a natural phenomenon due to changes in climate. The factors reported by the stakeholders as reasons for water quality deterioration were livestock grazing, erosion, and human activity. Table 6 summarizes stakeholder descriptions and perceived ecosystem service losses in the LLRB.

4.3. Environmental flow requirement

The estimated EFR for “Excellent”, “Fair”, “Poor”, and “Degraded” conditions represented 50.3 %, 39.4 %, 27.2 %, and 13.6 % of the MAF during the 1953–1971 period of record, respectively. EFR from July to October, for the “Excellent” condition, was equivalent to MMF from the year 1953–1971 (Fig. 3). The attained EFR represented 42.8 % of MAF of the respective period (1953–1971). On annual average, this flow satisfied an EFR “Fair” condition at 85.5 m^3/s, but when calculated monthly, EFR decreased from June to November with September to November conditions falling into the “Degraded” category.

4.4. Present and future water demands

In areas where irrigated agriculture was the major water-use sector, accounting for 86.8 % of the total demand, the current total annual water demand by agriculture, livestock, and domestic sectors was estimated to be 226.5×10^6 m^3. The domestic and livestock sectors accounted for 10.8 % and 2.4 % of water demand, respectively. The annual water demand was highest between November and January. Two low-demand periods were observed between February and April, and August and October (Fig. 4). The variation of water

Table 6
Present Ecological Status (PES), stakeholder descriptions, and Perception of Ecosystem Service Loss (PESL) in the Lower Limpopo River Basin.

Site	PES	Stakeholder description	PESL
Mabalane	B	The flow regime of the river has changed over time. Water shortages seen between August and October.	High
Guijá	C	The siltation of the river increased due to livestock activity. Water flow reductions observed mainly between August and September.	Medium
Chaimite	B	Water shortage was observed annually from August to September, and salinity problems occur due to the increases in water abstraction.	Medium
Chibuto	A/B	Dysconnectivity of the river was observed in dry years. The salinity of the water and erosion of the river were also observed. There was more flow reduction of the river compared to the colonial period from August to November.	High
Xai- Xai	B/C	There was no problem of water shortage, and no change of normal regime of the water, although there were problems of salinity (from June to September) and turbidities of the river.	Low

NOTE: State **A** signifies unmodified or natural. State **B** signifies largely natural with few modifications, a small change in natural habitats and biota may have taken place but the ecosystem functions are essentially unchanged. State **C** signifies moderately modified, a loss and change of natural habitat and biota have occurred, but the basic ecosystem functions are still predominantly unchanged (Kleynhans and Louw, 2008).

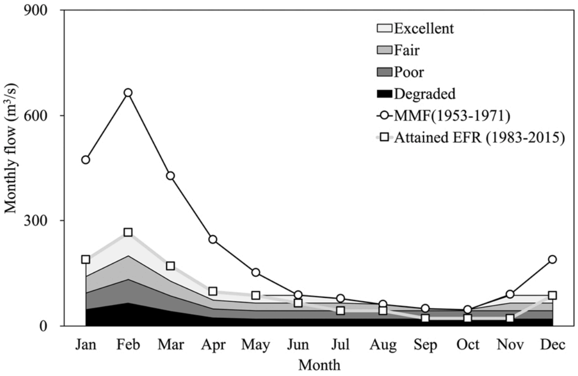

Fig. 3. Comparison between attained environmental flow requirement (Attained EFR) from 1983 to 2015 and EFR river conditions in natural regime estimated from 1953 to 1971 river discharges.

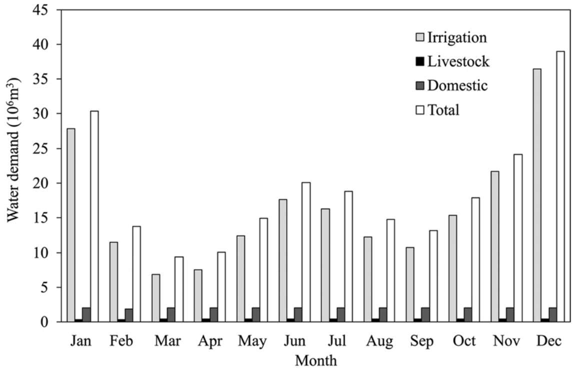

Fig. 4. Monthly trend of water demand in Lower Limpopo River basin (LLRB), based on the statistical information in 2015.

demand within the year is mainly due to cropping schedules (Fig. 5). From April to September agricultural production depends entirely on irrigation. The estimated future water demand was 4.9 times larger compared to the current water demand. The water demands of irrigated agriculture, livestock, and domestic are expected increase 5.4, 1.4, and 1.5 times, respectively (Fig. 6).

4.5. Incompatibilities between human and ecosystem water needs

BWA in the LLRB was estimated from 1953 to 1971 water discharge data collected before Massingir dam construction (i.e., pre-development natural flow regime). The mean BWA for the LLRB was determined to be 332.7 × 10^6 m^3 and represents the potential monthly availability of water in the basin. BWA is highest from December to April which is 90.2 % (Fig. 7). The 2015 BWF was 5.5 % of the BWA.

The LLRB annual $S_{quantity}$ index value for 2015 was 0.05 indicating there was sufficient water to meet anthropogenic consumption needs (Table 7). When calculated by month, the indicator showed deficits between August and October. The annual $S_{quantity}$ assessment indicated that the consumptive water for anthropogenic activities was 0.05 times the annual BWA when the EFRs are maintained under "Fair" conditions. Similarly, the July and November values suggest that the water consumptive use for anthropogenic activities was 0.48 and 0.37 times of the BWA, respectively. It means anthropogenic uses in July and November are nearly 50 % and 40 % of the BWAs, and any increased water abstractions during the months will intensify the competition between human water needs and EFRs. By 2035 the annual water scarcity value is expected to increase five times that of 2015, but still remain lower than 1. On an annual basis, there is enough water to meet the anthropogenic water demands in LLRB. However, the period of incompatibility will expand from June to November, and also anthropogenic uses will reach approximately 70 % of BWA in December in the future. Thus, more than half of the year will face no water availability to meet EFRs of "Fair" condition in the future.

5. Discussion

According to International Water Management Institute (IWMI) (2005), it was reported that 60–80 % of annual natural flow was necessary to maintain a river in a "pristine" state. In the case of LLRB, it was found that at least 50.3 % of MAF was necessary to maintain "Excellent" EFR conditions, based on pre-development river discharge data. The post-development period required 69.5 % of MAF for the same criteria. Currently it is impossible to attain an "Excellent" EFR condition for the LLRB. However, when EFR target

District	Crop type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mabalane	Maize1	■	■								■	■	■
	Maize2				■	■	■	■	■				
	Cabbage				■	■	■	■	■	■			
	Been				■	■	■	■					
	Tomato				■	■	■	■	■	■			
Chokwe	Maize1	■	■								■	■	■
	Maize2				■	■	■	■	■				
	Cabbage				■	■	■	■	■	■			
	Been				■	■	■	■					
	Tomato1	■							■	■	■	■	■
	Tomato2				■	■	■	■	■	■			
	Banana	■	■	■	■	■	■	■	■	■	■	■	■
	Rice	■	■	■	■						■	■	■
Guijá	Maize1	■	■								■	■	■
	Maize2				■	■	■	■	■				
	Cabbage				■	■	■	■	■	■			
	Been				■	■	■	■					
	Tomato1	■							■	■	■	■	■
	Tomato2				■	■	■	■	■	■			
	Banana	■	■	■	■	■	■	■	■	■	■	■	■
Chibuto	Maize1	■	■								■	■	■
	Maize2			■	■	■	■	■	■				
	Been			■	■	■	■	■					
	Tomato			■	■	■	■	■	■	■			
Xai-Xai	Maize1	■	■								■	■	■
	Maize2					■	■	■					
	Cabbage				■		■	■	■	■			
	Been				■	■	■	■					
	Rice	■	■	■						■	■	■	■

Fig. 5. Major crops and timing of irrigation in Lower Limpopo River basin (LLRB).

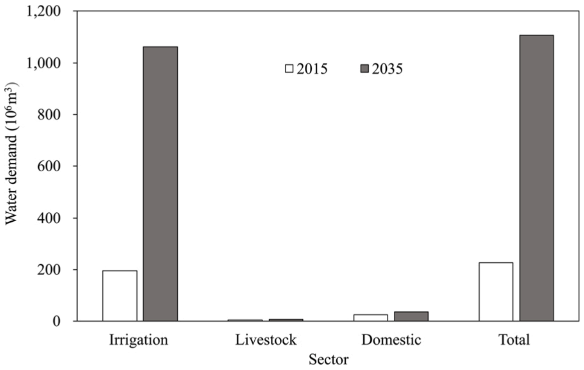

Fig. 6. Comparison of the present and future water demands in each sector.

conditions are set to “Fair”, MAF calculated from the attained EFR satisfy the criteria. This finding agrees with a result by Aurecon AMEI (Pty) Ltd (2013). That study predicted a significant annual surplus in LLRB resulting from the Massingir Dam project. While the predicted yield was not fully utilized, the provision of EFRs at the sub-basin level would reduce available yield and hence, decrease existing water surplus.

Although the analysis on an annual basis concluded that the LLRB discharge was enough water to maintain “Fair” EFRs, the conclusion did not accurately represent observed LLRB conditions. Pastor et al. (2014) found that in local studies the average the EFR was approximately 40 % of MAF and that water withdrawals were not possible during the low-flow season. Water conservation measures are therefore especially important during the low-flow season in order to preserve ecosystem function, for example ensuring fish survival to support fisheries and maintaining estuaries to support water quality through biofiltering. According to a fisherman that was interviewed, the critical period of LLRB fishing activity is from August to November. Fishing will be significantly affected if water

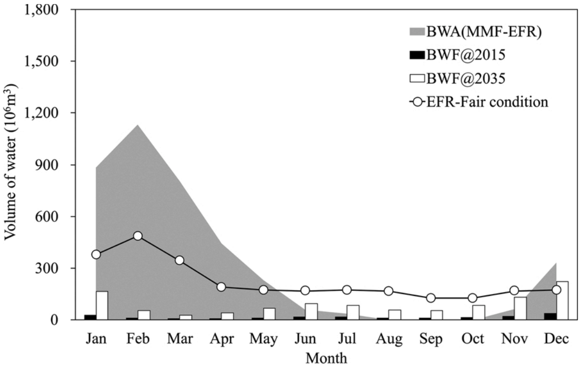

Fig. 7. The relation of monthly blue water availability (BWA) in Lower Limpopo River basin (LLRB) and monthly blue water footprint (BWF) in the years of 2015 and 2035.

Table 7
Estimated water scarcity calculated for 2015 and 2035 in Lower Limpopo River basin.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
$S_{quantity2015}$	0.03	0.01	0.01	0.02	0.06	0.32	0.48	$+\infty$	$+\infty$	$+\infty$	0.37	0.11	0.05
$S_{quantity2035}$	0.19	0.05	0.04	0.09	0.30	**1.57**	**2.29**	$+\infty$	$+\infty$	$+\infty$	**2.12**	0.66	0.27

for maintaining the ecological integrity in the Limpopo River is not ensured. At the same time, crop production will be affected if irrigation water is not available from September to November, the initial stage of first season crop production. The perceived high loss of ecosystem services in Mabalane was due to water shortage in the region. In this area there is no infrastructure to store water; the district depends on solely upon discharge from upstream countries. Water volumes in the lower parts of the LLRB depend upon the Elephant River which is regulated by the Massingir Dam. Downstream at Xai-Xai, water shortage was not an issue, however high salinity provides evidence that river flows are not enough to prevent seawater intrusion. Aurecon AMEI (Pty) Ltd (2013) reported that small scale farmers on the floodplain are beginning to see salinity increases in irrigation water.

FAO-SAFR (2004) reported that the LRB has a highly variable and unreliable flow. The river is intermittent with peak flows in February followed by low flow from May to early November. Our study showed about 78 % of LLRB flow occurred between December and April in both of pre-development (1953–1971) and post-development (1983–2015) periods. High flow variability explains the difference between annual water scarcity and monthly water scarcity illustrating the importance of river flow seasonality when making sustainability assessments. Hoekstra et al. (2012) reported that analysis of BWA on an annual basis might provide an incomplete and misleading view of BWA in watersheds where the majority of annual runoff occurs within few weeks or months and drought conditions dominate other parts of the year.

Upon examining the LLRB 2015 water demand, it was determined that there was not enough water to meet human water consumption from August to October while maintaining a “Fair” EFR condition. PES estimated from the assessment of the stream and riparian zone habitat integrity did not include local stakeholder’s perceptions. It is therefore not surprising that the PES score for the Mabalane, Chibuto, and Xai-Xai sites did not agree with PESL assessments (Table 6). This fact reflected the priority of river components which the stakeholders considered for carrying on their activities. In Mabalane, for example, the PES status was categorized as “B” indicating the site is largely natural with few modifications and the ecosystem functions are essentially unchanged. However, PESL was “High” indicating stakeholders perceive a strong loss of ecosystem services. As agriculture was major activity there, interviewees such as farmers strongly paid attention to water quantity and their perceptions reflected to the results of the questionnaire survey (Photo 2).

Stakeholder interviews showed perceived water shortages occurred mainly from August to November. Also, perceived loss of the ecosystem services varied from medium to high in these months. This analysis agrees with the stakeholder perception. However, the length of the period from August to October did not agree with a previous study conducted by Hoekstra et al. (2012) in the larger LRB. They found that the LRB faced severe water scarcity from July to November through their global water scarcity study. This difference in results is attributed to the difference in water scarcity indices, the environmental flow estimation approach, and study area size. According to Liu et al. (2015), Hoekstra et al. (2012) assumed EFR to be 80 % of the total water resources in the assessment of global water quantity scarcity. This assumption is simplistic because it does not consider the complexity of EFR and leads to an overestimate of the quantity-based water scarcity problem.

Even if annual water availability does not change, increased anthropogenic water demand will expand within-year period of water scarcity. Vilanculos and Macuácua (2009) reported that in 2025 the water demand in LRB at in Mozambique is projected to increase almost fourfold over the present water demand and the projected water availability will be more than the double that of demand. They concluded that it will be possible to satisfy the water needs in the basin. However, future water demand and availability was calculated on a yearly basis and monthly scarcity was not considered. Richter et al. (2003) pointed out that areas of potential incompatibility must

Photo 2. An interview in a farmland close to Limpopo river in Mabalane.

be examined both within and among years. Within-year evaluations will reveal the specific months or seasons during which ecosystem flow requirements are likely not to be met. This analysis shows, in 2035 the annual water scarcity will increase five times, compared to 2015, and the period of incompatibility will expand from June to November, mainly due to increased water abstraction for human purposes.

Das Gupta (2008) affirmed that the objective in implementing environmental flows is not to return rivers their natural state but to establish environmental needs of aquatic ecosystems so that these needs can be considered along with the social and economic needs when decisions are being made with regard to water uses and water allocations. Less water will be available to meet the water need for the environment due to the increase of water demand, and this may create tension among water users. To prevent this situation, water managers in the LLRB should focus mainly on agricultural irrigation, the main driver of water demand pressure. Attention must also be given to monthly water demand and availability.

6. Limitation of the study

According to Liu et al. (2015), the $S_{quantity}$ indicator is more suitable for large scale, quick, approximate assessments of general variation information across regions. For detailed assessments, local factors such as small-scale water consumptions and water allocation manners must be included. Also, the index does not account for green water resources; the amount of water from precipitation that, after having been stored in the root zone of the soil, is either lost by evapotranspiration or incorporated by plants. Moreover, the calculation of future LLRB water demand was based on the current cultivated crop patterns and potential planned areas which could change over time due to social factors. In addition, different types of environmental flow assessment (Tharme, 2003) are necessary by using such as more detail hydrological methods (e.g. Shaeri Karimi et al., 2012; Mohmood et al., 2020), hydraulic rating methods (e.g. Gippel and Stewardson, 1998; Liu and Men, 2007; Men, 2011), habitat simulation methods (e.g. Parasiewicz, 2001; Maddock et al., 2016; Sedighkia et al., 2017, 2021), holistic approaches (e.g. Hughes, 1999; Poff et al., 2010), if specific species and sites for the target biota need to be considered for conservation in the aquatic ecosystems with several levels of spatial and temporal resolutions.

7. Conclusions

This study assessed the sustainability of LLRB by EFRs from the aspect of river water volumes. Findings are summarized as follows:

- Currently, annual water shortages occur between August and October and are the main concern of local stakeholders.
- Maintaining an “Excellent” EFR (i.e., 50 % of natural flow) condition is not possible due to socioeconomic water needs but a “Fair” condition (i.e., 39 % of natural flow) may be achieved with careful management.
- When calculated on an annual basis, the $S_{quantity}$ indicator showed that there was / will be sufficient water volume to meet water the consumption needs of 2015 and 2035.
- When calculated on a monthly basis, the $S_{quantity}$ indicator showed that there was not enough water to meet human water consumption from August to October in 2015 and this period will expand from June to November due to projected increases in water demand.
- High variability in river flow suggests the need to determine monthly rather than annual water availability estimates.
- Agricultural irrigation dominates water use in the LLRB and must be effectively managed to ensure EFR sustainability and the ecosystem services they provide.

To prevent the potential water conflict among local LLRB stakeholders, it is recommended to focus mainly on the agricultural irrigation sector when considering management options. In order to determine realistic EFR values, additional investigations are necessary to obtain data on needs of multiple river ecosystems. Finally, it is necessary to involve expert knowledge from different scientific areas for assessing the ecological state of the LLRB in detail.

Author contributions

Osvaldo Silva Zefanias NHASSENGO: Conceptualization, Methodology, Investigation, Data Curation, Visualization, Writing - Original Draft

Hiroaki SOMURA: Conceptualization, Methodology, Resources, Supervision, Project administration, Visualization, Writing - Review & Editing

June WOLFE, III: Visualization, Writing - Review & Editing.

Declaration of Competing Interest

There are no conflicts of interest to declare.

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Appendix A. Supplementary data

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References

Administração Regional de Águas do Sul, 2017. Irrigation Development Plan and Small and Medium Enterprise Development Plan in the Irrigated Agriculture Chain, Republic of Mozambique (unpublished report).

African Water Facility, African Development Bank, 2014. Mozambique Feasibility Studies for Building Climate Resilience of. Owas/Awf/Gecl/Departments, Mozambique. https://www.afdb.org/fileadmin/uploads/afdb/Documents/Project-and-Operations/Mozambique-Approved-_AR-Feasibility_Studies_for_Building_Climate_Resilience_of_Limpopo_Basin_-_12_2014.pdf.

Alexandratos, N., Bruinsma, J., 2012. World Agriculture towards 2030/2050: the 2012 Revision. ESA Working Paper No. 12-03. FAO, Rome. http://www.fao.org/3/a-ap106e.pdf/.

Arthington, A., Bhaduri, A., Bunn, S., Jackson, S., Tharme, R., Tickner, D., Young, B., Acreman, M., Baker, N., Capon, S., Horne, A., Kendy, E., McClain, M., Poff, N., Richter, B., Ward, S., 2018. The brisbane declaration and global action agenda on environmental flows (2018). Front. Environ. Sci. 6, 1–15. https://doi.org/10.3389/fenvs.2018.00045.

Ashton, P.J., Love, D., Mahachi, H., Dirks, P.H.G.M., 2001. An overview of the impact of mining and mineral processing operations on Water resources and Water quality in the Zambezi, Limpopo and olifants catchments in Southern Africa. Contract Report to the Mining, Minerals and Sustainable Development (Southern Africa) Project, by SIR Environmentek, Pretoria, South Africa and Geology Department. Uni. of Zimbabwe, Harare, Zimbabwe. Report No. ENV-P-C 2001-042. xvi + 336 pp.

Aurecon AMEI (Pty) Ltd, 2013. Limpopo River Basin Monograph LRBMS-81137945 Final Monograph Report No. 8520. https://dsc.duq.edu/cgi/viewcontent.cgi?article=1011&context=limpopo-policy.

Bangira, C., Manyevere, A., 2009. Baseline Report on the Soils of the Limpopo River Basin, a Contribution to the Challenge Program on Water and Food Project 17 "Integrated Water Resource Management for Improved Rural Livelihoods: Managing Risk, Mitigating Drought and Improving Water Productivity in the Water Scarce Limpopo Basin". WaterNet Working Paper 8. Water Net, Harare. https://assets.publishing.service.gov.uk/media/57a08b60ed915d3cfd000cb4/WP8-LimpopoSoils.pdf.

Barbarossa, V., Schmitt, R.J., Huijbregts, M.A., Zarfl, C., King, H., Schipper, A.M., 2020. Impacts of current and future large dams on the geographic range connectivity of freshwater fish worldwide. Proc. Nat. Acad. Sci. United Sci. Am. 117, 3648–3655. https://doi.org/10.1073/pnas.1912776117.

Biemans, H., Haddeland, I., Kabat, P., Ludwig, F., Hutjes, R.W.A., Heinke, J., von Bloh, W., Gerten, D., 2011. Impact of reservoirs on river discharge and irrigation water supply during the 20th century. Water Resour. Res. 47, W03509. https://doi.org/10.1029/2009WR008929.

Boroto, R.A.J., Görgens, A.H.M., 1999. Hydrological Modelling of the Limpopo River Main Stem. Report by Department of Civil Engineering, University of Stellenbosch and Ninham Shand Consulting Engineers, to Department of Water Affairs & Forestry. DWAF Report No. PA000/00/0399.105 pp.

Brito, R., Famba, S., Munguambe, P., Ibraimo, N., Julaia, C., 2009. Profile of the Limpopo Basin in Mozambique, Contribution to the Challenge Program on Water and Food Project 17 "Integrated Water Resource Management for Improved Rural Livelihoods: Managing Risk, Mitigating Drought and Improving Water Productivity in the Water Scarce Limpopo Basin". WaterNet Working Paper 11. WaterNet, Harare. https://assets.publishing.service.gov.uk/media/57a08b47ed915d622c000be7/WP11-Mozambique.pdf.

Costanza, R., 2000. Social goals and the valuation of ecosystem services. Ecosystems 3, 4–10. https://doi.org/10.1007/s100210000002.

Das Gupta, A., 2008. Implication of environmental flows in river basin management. Phys. Chem. Earth Parts A/b/c 33 (5), 298–303. https://doi.org/10.1016/j.pce.2008.02.004.

De Groot, R.S., Wilson, M.A., Boumans, R.M.J., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecol. Econ. 41, 393–408. https://doi.org/10.1016/S0921-8009(02)00089-7.

Dyson, M., Bergkamp, G., Scanlon, J., 2008. Flow- the essentials of environmental flows. Gland, Switzerland: IUCN. Reprint, Gland, Switzerland: IUCN. Series: WANI Toolkit, 2nd ed. ISBN: 2-8317-0725-0.

FAO-SAFR, 2004. Drought Impact Mitigation and Prevention in the Limpopo River Basin a Situation Analysis. (Proceedings of the Land and Water Discussion Paper 4 in. Food and Agriculture Organization of the United Nations, Rome. ISSN 1729-0554.

Forslund, A., et al., 2009. Securing Water for Ecosystems and Human Well-being: The Importance of Environmental Flows. Swedish Water House Report 24. SIWI. ISBN: 978-91-975872-4-2.

Freire, P.R., 2013. Integridade Ambiental De Corpos D' Água : Degradação Ambiental, Funções Ecossistêmicas E Perda De Serviços Ecossistêmicos No Baixo São Francisco. Master thesis. Universidade Federal da Bahia Escola Politécnica. http://repositorio.ufba.br/ri/handle/ri/14227.

Gippel, C.J., Stewardson, M.J., 1998. Use of wetted perimeter in defining minimum environmental flows. Regul. Rivers: Res. Mgmt. 14, 53–67. https://doi.org/10.1002/(SICI)1099-1646(199801/02)14:1<53::AID-RRR476>3.0.CO;2-Z.

Graham, M., Louw, M.D., 2009. Module G: EcoClassification and EcoStatus Determination in River EcoClassification: Manual for Index of Hbitat Integrity (Section2, Model Photo Guide, Version 2), WRC Report No. TT378/09, Republic of South Africa.

Grand River Conservation Authority, Parish Geomorphic Trout Unlimited Canada, University of Guelph, University of Waterloo. (2017). Establishing Environmental Flow requirements for selected streams in the grand river watershed Pilot Project. https://www.grandriver.ca/en/index.aspx (View date: 7th.11.2017).

Hipolito, J.R., Vaz, A.C., 2011. Hidrologia E Recursos Hídricos, Lisboa, Instituto Superior Técnico. 1 ^{a} Edição. Lisboa Portugal IST Press. ISBN: 978-972-8469-86-3.

Hirji, R., Mackay, H., Maro, P., 2002. Defining and Mainstreaming Environmental Sustainability in Water Resources Management in Southern Africa. – a Summary. SADC, IUCN, SARDC, World Bank, Maseru/Harare/Washington DC.

Hoekstra, A.Y., Chapagain, A.K., 2007. Water footprints of nations: water use by people as a function of their consumption pattern. Water Res. Manag. 21, 35–48. https://doi.org/10.1007/s11269-006-9039-x.

Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2011. The Water Footprint Assessment Manual: Setting the Global Standard. Earthscan Press, London, UK. ISBN: 978-91-975872-4-2.

Hoekstra, A.Y., Mekonnen, M.M., Chapagain, A.K., Mathews, R.E., Richter, B.D., 2012. Global monthly water scarcity: blue water footprints versus blue water availability. PLoS One 7 (2), e32688. https://doi.org/10.1371/journal.pone.0032688.

Hughes, D., 1999. Towards the incorporation of magnitude-frequency concepts into the building block methodology used for quantifying ecological flow requirements of South African rivers. Water Sa 25, 279–284.

International Water Management Institute (IWMI), 2005. Environmental Flows: Planning for Environmental Water Allocation. Colombo, 6p. [IWMI Water Policy Briefing 15].. International Water Management Institute (IWMI), Sri Lanka https://www.iwmi.cgiar.org/publications/briefs/water-policy-briefs/iwmi-water-policy-briefing-15/.

Jayasiri, M.M., Dayawansa, N.D., Gunawardena, E.R., 2015. Comparison of methods to assess environmental flows: A Review. In: International Research Symposium on Engineering Advancements. SAITM. Malabe, Sri Lanka 2015, pp. 46–49.

Kleynhans, C.J.A., 1996. Qualitative procedure for the assessment of the habitat integrity status of the Luvuvhu River (Limpopo system, South Africa). J. Aquat. Ecosyst. Health 5, 41–54. https://doi.org/10.1007/BF00691728.

Kleynhans, C.J., Louw, M.D., 2008. Module A: EcoClassification and EcoStatus Determination in River EcoClassification: Manual for EcoStatus Determination (version 2). Joint Water Research Commission and Department of Water Affairs and Forestry report. https://doi.org/10.13140/RG.2.1.1728.3286. WRC Report No. TT 329/08.

Kroes, J.G., van Dam, J.C., Bartholomeus, R.P., Groenendijk, P., Heinen, M., Hendriks, R.F.A., Mulder, H.M., Supit, I., van Walsum, P.E.V., 2017. SWAP Version 4; Theory Description and User Manual. Wageningen, Wageningen Environmental Research, Report 2780. http://library.wur.nl/WebQuery/wurpubs/fulltext/416321.

Liu, C.M., Men, B.H., 2007. An ecological hydraulic radius approach to estimate the instream ecological water requirement. Prog. Nat. Sci. 17 (3), 320–327. https://doi.org/10.1080/10020070612331343264.

Liu, J., Liu, Q., Yang, H., 2015. Assessing Water Scarcity by Simultaneously Considering Environmental Flow Requirements, Water Quantity, and Water Quality. Elsevier Ltd. http://creativecommons.org/licenses/by/4.0.

Maddock, I., et al., 2016. Environmental flows: habitat modelling. In: Finlayson, C. (Ed.), The Wetland Book. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-6172-8_345-2.

Men, B.H., 2011. Ecological Hydraulics radius model for estimating instream ecological water requirement: a case application. Appl. Mech. Mater. 71–78, 2497–2500. https://doi.org/10.4028/www.scientific.net/amm.71-78.2497.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC. ISBN 1-59726-040-041.

Mohmood, R., Jia, S., Lv, A., Zhu, W., 2020. A preliminary assessment of environmental flow in the three rivers' source region, Qinghai Tibetan Plateau, China and suggestions. Ecol. Eng. 144, 105709 https://doi.org/10.1016/j.ecoleng.2019.105709.

National Institute of Statistics I.N.E, 1997. Population Cense and Projection, Mozambique. http://www.ine.gov.mz.

OECD, 2012. OECD Environmental Outlook to 2050: The Consequences of Inaction. OECD Publishing, Paris. https://doi.org/10.1787/9789264122246-en.

Parasiewicz, P., 2001. MesoHABSIM: a concept for application of instream flow models in river restoration planning. Fisheries 26 (9), 6–13. https://doi.org/10.1577/1548-8446(2001)026<0006:M>2.0.CO;2.

Pastor, A.V., Ludwig, F., Biemans, H., Hoff, H., Kabat, P., 2014. Accounting for environmental flow requirements in global water assessments. Hydrol. Earth Syst. Sci. Discuss. 18, 5041–5059. https://doi.org/10.5194/hess-18-5041-2014.

Poff, N.L., Richter, B.D., Arthington, A.H., Bunn, S.E., Naiman, R.J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B.P., Freeman, M.C., Henriksen, J., Jacobson, R.B., Kennen, J.G., Merritt, D.M., O'Keeffe, J.H., Olden, J.D., Rogers, K., Tharme, R.E., Warner, A., 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshw. Biol. 55, 147–170. https://doi.org/10.1111/j.1365-2427.2009.02204.x.

Richter, B.D., Wigington, R., David, H.L., Robert, W., 2003. Ecologically sustainable Water management. In: Applications, E. (Ed.), Ecological Society of America. https://doi.org/10.1890/1051-0761(2003)013[0206:ESWMMR]2.0.CO;2.

Rockström, J., Falkenmark, M., Allan, T., Folke, C., Gordon, L., Jägerskog, A., Kummu, M., Lannerstad, M., Meybeck, M., Molden, D., Postel, S., Savenije, H., Svedin, U., Turton, A., Varis, O., 2014. The unfolding water drama in the Anthropocene: towards a resilience-based perspective on water for global sustainability. Ecohydrology 7 (5), 1249–1261. https://doi.org/10.1002/eco.1562.

Sedighkia, M., Ayyoubzadeh, S.A., Esmaeili, M.H., 2017. Habitat simu-lation technique as a powerful tool for instream flow needs assess-ment and river ecosystem management. Environ. Energy Econ. Res 1 (2), 171–182. https://doi.org/10.22097/eeer.2017.47244.

Sedighkia, M., Abdoli, A., Datta, B., 2021. Optimizing monthly ecological flow regime by a coupled fuzzy physical habitat simulation–genetic algorithm method. Environ. Syst. Decis. https://doi.org/10.1007/s10669-021-09809-z.

Shaeri Karimi, S., Yasi, M., Eslamian, S., 2012. Use of hydrological methods for assessment of environmental flow in a river reach. Int. J. Environ. Sci. Technol. (Tehran) 9, 549–558. https://doi.org/10.1007/s13762-012-0062-6.

Southern African Research and Documentation Centre, 2003. Limpopo River Basin-factsheet 1 - the Limpopo River. https://www.sardc.net/en/wp-content/uploads/Limpopo/en/Limpopo1.pdf.

Tharme, R.E., 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River Res. Applic. 19, 397–441. https://doi.org/10.1002/rra.736.

Tompkins, J., Hearnshaw, E.J., Cullen, R., 2011. Evaluating the sustainability of impounded river systems and the cost-effectiveness of dam projects: an ecosystem services approach abstract. In: 55th Annual AARES National Conference Melbourne. Victoria. Australian Agricultural and Resource Economics Society. https://doi.org/10.22004/ag.econ.100720.

UN-HABITAT/UNEP, 2007. Limpopo Basin Strategic Plan for Reducing Vulnerability to Floods and Droughts. Draft for Discussion with Riparian Governments. pp.23. http://www.limpopo.riverawarenesskit.org/LIMPOPORAK_COM/_SYSTEM/DMSSTORAGE/3471EN/UNEP_UN_HABITAT_GEF2007_LIMPOPO.PDF.

Van der Zaag, P., Juizo, D., Vilanculos, A., Bolding, A., Uiterweer, N.P., 2010. Does the Limpopo River Basin have sufficient water for massive irrigation development in the plains of Mozambique? Phys. Chem. Earth 35 (13–14), 832–837. https://doi.org/10.1016/j.pce.2010.07.026.

Vilanculos, A., Macuácua, E., 2009. Final Report: Quantitative Analysis of Water Demand and Supply for Lower Limpopo Departamento Técnico Serviços De Recursos Hídricos: Sector De Hidrologia. ARA -Sul.

Vörösmarty, C., McIntyre, P., Gessner, M., et al., 2010. Global threats to human water security and river biodiversity. Nature 467, 555–561. https://doi.org/10.1038/nature09440 (2010).