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## A literature review on global and national evidences

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**DOI**
10.1016/j.envdev.2022.100758

**Publication date**
2022

**Document Version**
Final published version

**Published in**
Environmental Development

Environmental Development 44 (2022) 100758

Contents lists available at ScienceDirect

Environmental Development

journal homepage: www.elsevier.com/locate/envdev

# Environmental flow assessment and implications on sustainability of aquatic ecosystems in Ethiopia: A literature review on global and national evidences

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A R T I C L E I N F O

*Keywords:*
Aquatic ecosystem
Biodiversity
Ecosystem services
Environmental flow assessment methods
Ethiopia
Nile basin initiatives

A B S T R A C T

As part of water resources management policy, water resources projects undertake environmental flow assessments (EFA) to determine how much water should be maintained or released to the downstream part of rivers to protect the health of aquatic and riparian ecosystems and societal wellbeing. In Ethiopia, EFA is being undertaken mostly in relation to dam projects. Most of dam projects in Ethiopia consider the 95% exceedance probability flow (Q95) as acceptable for downstream releases, which does not consider the variable and dynamic nature of rivers or the impacts on societal livelihoods dependent on ecosystem services. This paper aims to explore the application of EFA in Ethiopia based on global and national experiences. The paper begins with an overview of the water resources and biodiversity that need protection; second, systematic review of the current status of application of EFA methodologies in Ethiopia; and finally, the main types of environmental flow methodologies available globally that can be utilized in different parts of the country were explored, with emphasis on projects and research endeavors. It is found that environmental flow is strongly considered in Ethiopia, which is critical as the country is a custodian to precious aquatic and riparian biodiversity resources which have national and global importance. However, it is found also that there is little research on the topic for advising appropriate EFA methodology application in Ethiopia. Thus, it is suggested a holistic approach of environmental flow assessment that can entertain all other types of methods in tropical highland rivers.

## 1. Introduction

The preservation of natural hydrological regimes is critical in developing countries such as Ethiopia, where a substantial portion of the population's subsistence is heavily reliant on ecosystem services (Reitberger and McCartney, 2011). As part of a water resources

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https://doi.org/10.1016/j.envdev.2022.100758
Received 26 April 2022; Received in revised form 23 September 2022; Accepted 26 September 2022
Available online 30 September 2022
2211-4645/

management policy, a water resources project undertakes environmental flow assessment (EFA) to determine how much water should be maintained or released to the downstream part of the river to protect the health of the aquatic and riparian ecology and societal wellbeing (MOWR, 1999, Birhane, 2002; Awulachew et al., 2007; Kloos and Legesse, 2010; Martinez-Santos et al., 2014). A study showed that in Ethiopia, as part of the Environmental Impact Assessment (EIA) especially for projects of water abstraction, EFA is being undertaken (Abebe et al., 2007). There are different EFA methodologies, and the reliability of the methods depends on the extent of parameters (ecosystem components) considered and scale of water resources development (Zalucki and Arthington, 1998).

This paper aims to provide information on the application of EFA in Ethiopia based on global, regional and national evidence and outline suggestions for further research. First, it makes an overview of the aquatic resources and biodiversity that need protection based on reviews of available state-of-the-art water resources and biodiversity literatures about Ethiopia and then, systematic review of the current status of application of EFA methodologies in Ethiopia. The systematic review considered the method by Cook et al. (1997) defining inclusion criteria of "Environmental flow" AND "Ethiopia" for retrieving literatures of peer-reviewed journals from the Google Scholar search engine. And, attributes were chosen in order to summarize the literatures found with the systematic review to ensure how the policy issues of Ethiopia related to EFA are considered, ensure which areas of the country are covered with EFA study and whether state-of-the-art EFA methods are being applied. Four attributes were mainly chosen: 1) year of publication, 2) the objectives/policy issues considered in the environmental flow research, 3) location of the study areas linking to the major basins of Ethiopia, and 4) the methodologies applied in the quantification of environmental flow requirement. In addition, this paper also reviewed and outlined the main types of environmental flow methodologies available globally and explores the extent to which they have been utilized in different parts of the country, with emphasis on projects and research activities.

## 2. Rationale for environmental flow assessment in Ethiopia

### 2.1. Freshwater aquatic ecosystems in Ethiopia

In Ethiopia, there are about 30 major lakes, 12 major river basins and over 70 major wetlands that are located in different ecological zones (EBI, 2021). About 122 billion cubic meter (BCM) runoff is generated annually from 10 river basins while the remaining two basins are dry (MOWR, 1999; Fisseha, 2003). The ground water potential is estimated to be 36 BCM (Kansal et al., 2014). Between 80 and 90% of Ethiopia's water resources is found in four river basins namely, Abay (Blue Nile), Tekeze, Baro Akobo, and Omo Gibe (MOWR, 1999). Several of the major rivers cross to neighboring countries; it has been estimated that 95% of Ethiopia's annual run-off flows out of the country in the trans-boundary rivers (OU, 2016). The wetland ecosystems of Ethiopia are home to an abundance of aquatic biodiversity; such as the Cheffa and Lake Tana basin floodplain wetlands in the North, Lake Zeway, Abaya and Chamo of the rift valley wetlands, and the Baro and the Dabus River wetlands in the western Ethiopia (Menbere and Menbere, 2018; Elias et al., 2019).

The occurrence of water in Ethiopia is highly variable where its accessibility and suitability vary from region to region (Kansal et al., 2014). The precipitation in the country is unevenly distributed making some regions water-deficit and others water-surplus. There are only about 29 large dams in Ethiopia with reservoir size of 0.0007–74 $km^3$, which are being used for either irrigation, drinking water, hydropower, fishing, siltation sink, flood control and/or multi-purpose (HATHAWAY, 2008). Water shortage is deeply rooted in the country, so reducing the frequency and/or severity of the adverse consequences of droughts, floods and excessive pollution are common goals of many water resources planning and management exercises (Loucks and Van Beek, 2005). Besides, environmental water requirement of aquatic ecosystem called for environmental flow assessment which supports the decision making for water allocation to the environment. Zalewski et al. (2010) recommended that European experience (Kędziora, 2010) may be able to assist in the transition to sustainability in Ethiopian lakes and river basins by improving ecosystem services in agricultural environments. Ecosystem services consist of flows of materials, energy, and information from natural capital stocks (such as trees, minerals, ecosystems, the atmosphere, etc.) which combine with manufactured and human capital services to produce human welfare (MEA, 2005). Water as aquatic ecosystem provides ecosystems services that include 4 broad categories such as: provision, regulating, supporting and cultural services (Costanza et al., 2014; MEA, 2005).

### 2.2. Aquatic and riparian biodiversity resources in Ethiopia

There are 188 fish species, 91 benthic and aquatic insects and 141 zooplankton species recorded so far in Ethiopia (EBI, 2021; Zegeye, 2017). The total number of woody species of Ethiopia is estimated to be 1017, out of which 29 tree species, 93 shrub species and 2 liana species are endemic and inhabit riparian ecosystems. Eighty percent of the Ethiopian people depend on traditional medicine for their health care (Abebe and Ayehu, 1993), and more than 95% of traditional medicinal preparations in Ethiopia are made from plants including herbaceous aquatic and riparian species (Geyid et al., 2005; Abebe, 1986).

In the Lake Tana basin only, rivers and wetlands surrounding the lake are the migration habitat of 27 in total and 15 unique species of Labeobarbus and *Clarias gariepinus* fish species (Nagelkerke and Sibbing, 1997; Shitaw et al., 2018). According to Shitaw et al. (2018), Goshu et al. (2010), Tewabe (2012), the three major fish families (Cichlidae, Clariidae and Cyprinidae) are widely distributed throughout the country. In addition, the twelve globally threatened bird species are recorded in the Shesher and Welala wetlands of Lake Tana which are part of the UNESCO Biosphere reserve areas (Aynalem and Bekele, 2008).

The major threats to aquatic and wetland wild animals are habitat loss and degradation, siltation as a result of catchment degradation, over-harvesting, unbalanced water utilization, change in water flow (flow modification), sand mining, draining of wetlands for other land uses, invasive alien species (IAS) and pollution (EBI, 2021; Kebede et al., 2017).

### 2.3. Quality of hydrological monitoring networks for water resources planning

Improved hydrological monitoring infrastructure yields more precise and timely decision-relevant data; and greatly helps in the management of water resources, improvement of disaster management, and more optimal water utilization among other benefits. In Ethiopia, there are about 500 flow gauging stations for 12 river basins which measure only flow (see Fig. 1); and only 74 stations equipped with stage sensor (radar, pressure, float) (MOWR, 2009). Water quality and other biological data like fish, macro-invertebrates, macrophytes, phytoplankton, zooplankton, coliforms and viruses are rarely measured, except occasional measurements by researchers/research institutes, students or projects.

According to the World Meteorological Organization (WMO, 2010), the density of a gauging stations network in a river basin is dependent on the data requirement and combinations of physical and climatic variables such as catchment area, highlands and low lands (see Table 1). Hence, the coverage of gauging station in Ethiopia is very limited as there are only 506 stations (72%) out of 700 recommended first-class water level stations for 1.13 million $km^2$ drainage area of Ethiopia. On top of this, Ministry of water, irrigation and electric (MOWIE, 2019) reported that the challenges in hydrological and water quality data collection, management and dissemination in Ethiopia are limited coverage of communication/telemetric systems for all basins; backward data recording systems; institutional problems such as a lack of strong linkage and coordination, absence of calibration laboratories for instruments, and insufficient support for logistical facilities such as vehicles, and budget; human resources; accessibility problems to critical sites (road network coverage); absence of appropriate databases; and problems of vandalism. These challenges are being addressed through modeling work to generate additional hydrological and limnological data and data processing for water resources planning and decision-making, such as maintaining environmental flows using hydrological methods in rivers for aquatic ecosystem conservation.

### 2.4. Environmental pressures in Ethiopia

#### 2.4.1. Hydrological Alteration

Reduced lake water level with its annual fluctuation and seasonal floods associated with high flows are becoming bigger in Ethiopia (Ligdi et al., 2010). The minimum and maximum lake level fluctuations of Lake Tana were roughly 2 m and 3.2 m, respectively, throughout the last 42 years (1965–2008), with the minimum lake level recorded during the period water from the lake was withdrawn for hydroelectric power production and released to a neighboring river called Beles as water transfer in 2002 (Minale and Rao, 2011; Dargahi and Setegn, 2011). In 2002 and 2003, after the construction of Chara-Chara weir, the water level of the lake was reduced to the extent that public transportation through the lake, serving more than one million people, was halted for 4 months (Tesfahun and Demissie, 2004). The lake level was as low as 1784.26 m (in 2003) which has dropped below the lowest historical value of the year 1961 (1785.34 m). The mean monthly values from May 2016 to September 2019 were computed and found to be in the range of 1.5–3.98 m (Dersseh et al., 2020). The increase in lake level has caused expansion of the invasive alien weed, water hyacinth (*Eichhornia crassipes*) in the lake causing tremendous ecological and socio-economic problems. Besides, the long flushing time (19 months) will not allow a fast decay of contaminating materials released into the lake, which implies that the lake is vulnerable to changes in external conditions (Dargahi and Setegn, 2011).

#### 2.4.2. Land use/cover change: case studies

About 35% of the total land area of Ethiopia was covered with natural high forests a century ago (Reusing, 1998). In 2000, it is

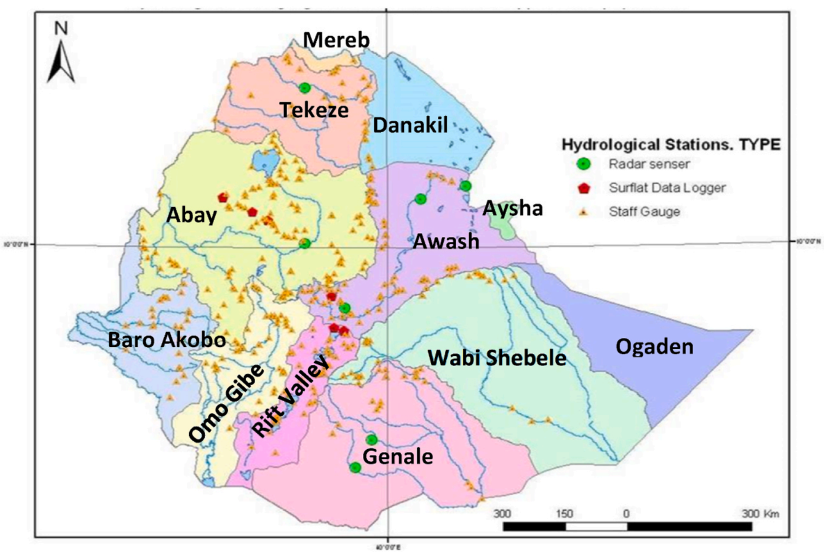


**Fig. 1.** Hydrological stations and basins of Ethiopia with different types of measurement equipment; adapted from MOWR (2009).

**Table 1**
Calculated gauging stations density of Ethiopia based on physiographic classes.

| Serial No. | Physiographic classes | Percentage cover | Area. $Km^2$ | Station Density standard (WMO, 2010) | Required station density |
|---|---|---|---|---|---|
| 1 | The western highlands and lowlands | 44 | 497,200 | | |
| 1.1 | Western highlands | 76.3 | 379,364 | 1000–1875 | 264 |
| 1.2 | Western lowlands | 23.7 | 117,836 | 1875 | 63 |
| 2 | The southeastern highlands and lowlands | 37 | 418,100 | | |
| 2.1 | Southeastern highlands | 46 | 192,326 | 1000–1875 | 134 |
| 2.2 | Southeastern lowlands | 54 | 225,774 | 1875 | 120 |
| 3 | The rift valley | 19 | 214,700 | 1875 | 115 |
| | | **Total** | **1,130,000** | | **696** |

estimated that Ethiopia left with a forest cover of 4% of its total land area (43,440 $km^2$); a shrinkage by 90% (Zegeye, 2017). Ethiopia's rate of natural forest cover deterioration is around average when considered to other east African countries (FAO, 2007). In Ethiopia, high forest cover decrease occurred between 1973 and 1990 from 54,410 $km^2$ to 45,055 $km^2$ or from 4.72% to 3.96% of the land area; which is estimated a deforestation rate of 1410 $km^2$ per year (Reusing, 1998). In the tropical highlands of Ethiopia, within the last 35 years more than 6.2% of the lake Tana sub-basin area was converted to other land covers (Minale and Rao, 2011). There is a marked expansion of agricultural land, bush land, and scrubbed grassland, whereas a noticeable reduction in grassland and shrubland among others (Ligdi et al., 2010). This showed consequent decreasing impact on the environmental flow or low flow of the rivers (Chakilu, G. & Moges, M., 2017). For example, in the Lake Tana sub-basin, cultivated land is being expanded at the expense of other ecologically sensitive land covers, such as forest lands (Abebe and Minale, 2017). According to Abebe and Minale (2017), about 312,887 ha of land in lake Tana subbasin was cultivated land in 1986, and expanded to 549,417 ha in 2013, which is resulted from deforestation and encroachment of wetlands and lake recession lands. Another study in the Gilgel Abay river which drains to the Lake Tana showed an increase of cultivated land by 33.79% over 25 years period (1986–2011) resulted an increase of stream flow and sediment yield by 5.87 $m^3/s$ and 62.78 $t/km^2$ respectively (Andualem and Gebremariam, 2015). This will cause in water quality deterioration of water bodies. Hence, restoration of forest cover, especially riparian and wetland vegetation, need consideration of environmental flows.

Recently, ESRI released a 10 m resolution land cover of the earth using sentinel-2 images from 2017 to 2021 (ESRI, 2022) in which Ethiopia has a land cover of 984,414 ha (0.87%) water, 25,200,800 ha (22.26%) wetland, 18,425,230 ha (16.28%) farmland, 2,020,704 ha (1.78%) built-up area, 2,110,416 ha (1.86%) bare land, 64,458,290 ha (56.94%) grassland with farmland and shrubs/bushes, and the rest (0.01) snow or cloud in 2021 (Fig. 2). The land cover of farmland increased by 1 million hectares between 2017 and 2021, which can have an impact on maintaining the environmental flow of river basins by increasing overland flow and decreasing base or low flow (supplementary material_LULC).

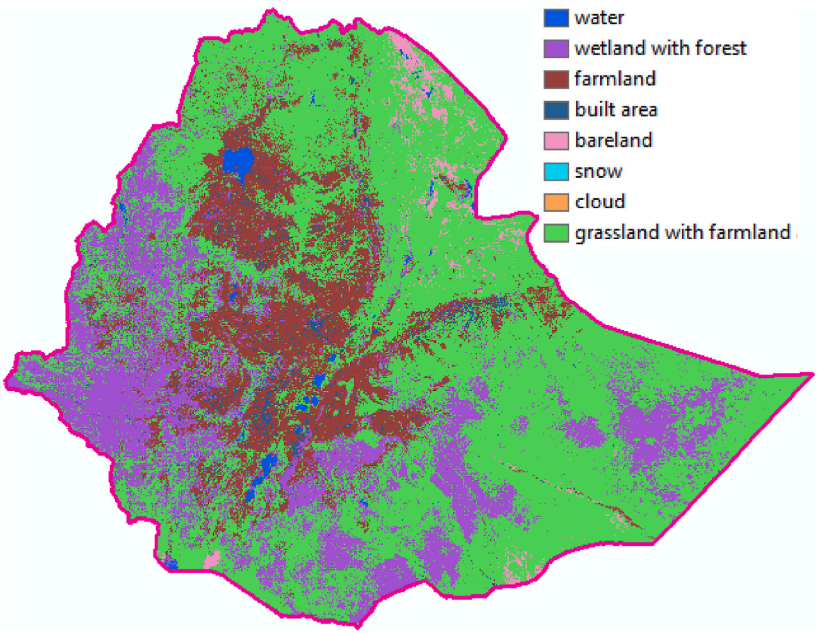


**Fig. 2.** Land cover map of Ethiopia in 2021 (source: ESRI (2022)). Note. This dataset is based on the dataset produced for the Dynamic World Project by National Geographic Society in partnership with Google and the World Resources Institute.

#### 2.4.3. Climate change: case studies

Studies have revealed that climate change will affect the water balance of Lake Tana and pose environmental risks unless proper water resource measures are implemented (Belete, 2014; Setegn et al., 2011). Projected changes in monthly precipitation and temperature in the Tana sub-basin from 15 GCMs (Global Climate Models-General Circulation Models) were analyzed and it was found that four of the nine GCMs indicated a significant decrease in annual stream flow for the 2080–2100 period (Setegn et al., 2011). The decrease in stream flows leads to drying of rivers and wetlands which are the breeding habitat for fish and other biota and also cause riparian vegetation to deteriorate. So, maintaining the low flow or environmental flows needs to be devised in conservation of the aquatic and riparian ecosystems (Tesfaye et al., 2020; Lasage et al., 2015).

#### 2.4.4. Population density

The Ethiopian highlands, consisting of around 45% of the total area of the country, contain four-fifths of the human and two-thirds of the livestock populations (Bielli et al., 2001). In the northern highlands of Ethiopia, as a result of rapidly increasing population, marginal lands such as wetlands and recession areas are being cultivated where there is serious land shortage and more than 90% of the land is used for agricultural purposes on a permanent basis (Ezra, 1997). Imbalances in aquatic ecosystems of river basins is the reflection of inappropriate land use practices because of human population growth and consequent resource competition (Shiel, 1996).

## 3. Development of environmental flow assessment methodologies globally and in the Nile Basin

### 3.1. Environmental flow assessment methodologies to date and applications for Ethiopia

There are different methodologies of undertaking environmental flow assessment (Acreman et al., 2014; McClain et al., 2014; King and Brown, 2010; Abebe et al., 2007; Tharme, 2003). King et al. (2008) indicated that there are generally four assessment approaches to determine environmental flow; these are: hydrological, hydraulic rating, habitat rating, and holistic. The hydrological method is the earliest one which is based solely on hydrological data that use summary statistics of flow. Then, hydraulic-rating methods were developed because of hydrological methods lacked sensitivity to individual rivers. Hydraulic-rating method uses field measurements to describe channel–discharge relationships. But, hydraulic-rating also failed to indicate the significance of changes in the measured physical conditions for the aquatic biota. This led to the development of habitat-rating approaches, which links simulations of local channel hydraulics over a range of discharges with data on the hydraulic conditions in which selected fish species are most frequently found. Now a days, with the development of knowledge of environmental flow concepts, the holistic approaches are established which advice on flows for maintenance of the whole ecosystem (Tables 2–5).

The four groups of EFA methodologies in different parts of the world (Poff et al., 2017; King et al., 2008; Tharme, 2003) are reviewed purposefully from different literatures and project reports. A total of nineteen (19) EFA methods were identified and selected which are actively being used in different ways in different countries that can be applicable for Ethiopia (Tables 2–5). Most of the holistic approaches are frameworks which can include one or more of the hydrologic or hydraulic or habitat simulation methods. Their relevance was sought decisively for Ethiopia based on the scale of water resources development projects, data availability and executability. Hence, in the following sections, applications of EFA methodologies are summarized and recommended for different scales of planning for tropical highland rivers of Ethiopia (Tables 2–5).

#### 3.1.1. Hydrological approach of EFA

Five hydrological EFA methods were reviewed. These are: Tennant/Montana method, flow duration curve analysis (FDCA), Texas method, Palau Basic Flow method (BFM), and Range of variability approach (RVA) and 7Q10 or 7Q2 method (Table 2).

#### 3.1.2. Hydraulic-rating approach of EFA

Three hydraulic-rating EFA methods were reviewed. These are: wetted perimeter curves method, habitat retention model, and hydraulic biotopes method (Table 3).

#### 3.1.3. Habitat-rating approach of EFA

Six habitat-rating EFA methods were reviewed. These are: physical habitat simulation (PHABSIM), the evaluation of habitat (EVHA) methodology, Computer Aided Simulation Model for Instream flow Requirements (CASIMIR), Riverine Community Habitat Assessment and Restoration Concept (RCHARC), ‘Habitat Evaluation Procedures’/‘Habitat suitability indices’ (HEP/HIS), and AVDEPTH habitat model (Table 4).

#### 3.1.4. Holistic approach of EFA

Five hydrological EFA methods were reviewed. These are: Building block methodology (BBM), Instream Flow Incremental Method (IFIM), Downstream Response to Imposed Flow Transformation (DRIFT), Ecological Limits of Hydrological Alteration (ELOHA), and Savanah processes or Expert Panel Assessment Method (EPAM) approach (Table 5).

### 3.2. NBI environmental flow management framework

For the first time in the Basin’s history, an all-inclusive basin-wide institution, The Nile Basin Initiative (NBI), was established, on 22nd February 1999, to provide a forum for consultation and coordination among the Basin States for the sustainable management and

**Table 2**
Summary of hydrological environmental flow assessment (EFA) methodologies (adopted from different literatures). Each EFA method is evaluated and recommended for Ethiopia based on data availability and executability. »-the same as above.

| Approach | Definition/Type | Usage and drawback | Recommendation for Ethiopia | | Country and Reference |
|---|---|---|---|---|---|
| | | | Data availability | Executability | |
| Hydrological | •Earliest method;<br>•Use single or multiple flow indices derived from historical flow records | •The simplest and quickest assessment techniques, applied in all world regions<br>•Dynamic nature of flow regime seldom addressed,<br>•May or may not be ecologically relevant, to advice on suitable flows, often for fish habitat | •Data available since 1970s for 70% of the major rivers.<br>•For lower order rivers, modeling and regionalization are needed | Appropriate at the planning level of water resource development; basin wide scoping level environmental flow assessment | |
| | Tennant/Montana method | •A standard-setting approach<br>•Fixed-percentage/proportion (minimum flow) i.e. %AAF, where 10% AAF = poor condition; 40% AAF = good dry season condition; 20% AAF = good wet season condition etc.<br>•10% AAF to sustain short-term survival habitat for most aquatic biota<br>•30% AAF to sustain good survival conditions for most aquatic life forms and general recreation.<br>•60% for most aquatic life forms during growth and the majority of recreational uses | » | Recommended for basin wide scoping level environmental flow assessment<br>Addresses environmental flows for fish, wildlife, recreation and related environmental resources<br>Potential for development of ecotype-specific methods | USA, (Tennant, 1976) |
| | Flow Duration Curve Analysis (FDCA); eg. Q95 method | •to derive percentage exceedance values associated with required suitable river conditions | » | Recommended for basin wide scoping level environmental flow assessment | Applied worldwide; (Gordon et al., 1992) |
| | Texas Method | •use variable percentages of the monthly median flow<br>•The percentages are calibrated to the different ecological zones, taking into account results from previous fish inventories and known life history requirements | »; but ecological data is scarce | Better than Tennant or Q95 methods; i.e. highly recommended taking in to account ecological data availability | Texas, USA; (Matthews and Bao, 1991) |
| | Palau Basic flow method (BFM) | •Spanish. Characteristic Basic Flow for a river type<br>•Using the simple moving average model<br>•For each year (10 years data), construct a matrix of every moving average from 1 to 100 points and take the minimum one<br>•the basic flow is where there is the largest relative increase when considering theconsecutive increase in moving averages 1 to 100 points | » | Recommended for flashier rivers; to find a more relevant low flow index than Q95 | Spain; (Dunbar et al., 1997) |
| | Range of variability approach (RVA)-IHA | •In an RVA analysis, the full range of pre-impact and post-impact flow data is compared dividing in to 3 percentile categories and measure changes in frequency of flows in these categories between the pre- and post-impact periods to understand flow alteration<br>•IHA software is used to analyze RVAs | » | Recommended for all kinds of highland rivers in Ethiopia with protection of the natural ecosystem is the primary objective | USA; (TNC, 2009) |
| | US-EPA 7Q10 or 7Q2 method; (Statistical low flow frequency method) | •a statistical low flow frequency analysis of the minimum mean daily flow during a given sample period of 7 days (duration) with in 10 or 2 years return period (frequency)<br>•Surface water toolbox by US-EPA | » | Recommended for dilution of waste water | Caissie et al. (2015) |

**Table 3**
Summary of hydraulic-rating EFA methodologies (adopted from different literatures). Each EFA method is evaluated and recommended for Ethiopia based on data availability and executability. »-the same as above.

| Approach | Definition/Type | Usage and drawback | Recommendation for Ethiopia | | Country and Reference |
|---|---|---|---|---|---|
| | | | Data availability | Executability | |
| Hydraulic rating | Use changes in hydraulic variables with discharge across cross-section(s) as biota habitat factors | • Usually targeted economically important fish species, where flows to facilitate fish spawning and passage.<br>•Failed to indicate the significance of changes in the measured physical conditions for the aquatic biota. | No readily available data for most of the cases except for gauging stations (70% coverage) | All of them applicable with extensive survey during a study. | |
| | Wetted perimeter curves method | • assumes that a direct relationship between wetted perimeter and fish habitat exists in streams<br>•wetted perimeter versus discharge<br>•useful for assessment of spawning flow<br>•not incremental; influenced by channel shape; doesn't consider depth; and no seasonal considerations | Readily available Hydraulic survey data of gauging stations can be used for major rivers. Lower order rivers need survey during a study | Recommended for assessment of spawning flows of rivers of known migratory fish habitats; with the objective of maximising macroinvertebrate production | Annear and Conder (1984) |
| | Habitat retention model | • assessing hydrological rules of thumb that describes their consequences for protection of the ecosystem (in terms of retention of physical habitat)<br>• the criteria consist of stream width, average depth, average velocity, and wetted perimeter | » | Recommended for assessment of spawning flows of rivers of known migratory fish habitats. | Snelder et al. (2011) |
| | Hydraulic biotopes | • Hydraulic biotopes are: riffles, runs, pools, glides, cascades, rapids and backwaters.<br>• Controlled by channel morphology, substrate and flow conditions | » | Recommended for assessment of conservation status in regulated rivers | Australia, UK; (Desai, 2012) |

development of the shared Nile Basin water and related resources for win-win benefits (NBI, 2022). The Nile Basin Initiative (NBI) is an intergovernmental partnership of 10 Nile Basin countries, namely Burundi, DR Congo, Egypt, Ethiopia, Kenya, Rwanda, South Sudan, The Sudan, Tanzania and Uganda. Eritrea participates as an observer.

As a key element of Integrated Water Resources Management (IWRM) in the Nile Basin, NBI has developed an environmental flows management framework based on the ELOHA (Ecological Limits Of Hydrological Alteration) framework and global best practices; and chose PROBFLO model as one of the best holistic methodologies to determine environmental flow requirement (NBI, 2016). The ELOHA framework is an open framework developed and accepted globally to ensure that all of the necessary factors that contribute to successful management of environmental flows are considered, and accommodates whatever models are suited to this goal (Poff et al., 2010). The new model that has been developed, called PROBFLO, brings together three internationally accepted and credible approaches i.e. the ELOHA framework, probability modeling in the form of Bayesian Networks and Regional Risk Assessments for assessing scenarios (O'Brien et al., 2018).

The NBI environmental flow management framework (NBI-EFMF) states seven procedural steps to undertake EFA:

- **Phase 1**: Situation Assessment and Alignment Process - in this phase information and plans, management objectives and assessment requirements are aligned.
- **Phase 2:** Governance and Resource Quality Objectives Setting - this phase ensures that local and regional E-flow governance requirements are considered/applied in Environmental flow (E-flow) assessments, and describes the vision and Resource Quality Objectives determination procedures.
- **Phase 3:** Hydrological Foundation - this phase includes the baseline evaluation/modeling of hydrology data for the site/regional E-flows assessments. *This phase usually forms the foundation phase of EFA method applications.* Available flow data, rainfall and evaporation data, water abstraction data, land use data and other information that may affect flows is used in this phase to characterize baseline flows and potentially describe any differences between these baseline flows and current flows.

**Table 4**
Summary of habitat-rating EFA methodologies (adopted from different literatures). Each EFA method is evaluated and recommended for Ethiopia based on data availability and executability. »-the same as above.

| Approach | Definition/Type | Usage and drawback | Recommendation for Ethiopia | | Country and Reference |
|---|---|---|---|---|---|
| | | | Data availability | Executability | |
| Habitat rating | Model quantity and suitability of physical habitat for target species under different flows; | • Integrate hydrological, hydraulic, biological response data.<br>• usually targeted economically important fish species, where flows to facilitate fish spawning and passage<br>• Habitat alone could not fully address ecosystem health | Readily available data is very few. Need survey during the study period | | |
| | Physical Habitat Simulation -PHABSIM model | • An integrated habitat simulation and analysis system<br>• Habitat-flow model: uses depth, wetted perimeter, velocity, weighted useable area (WUA). Uses habitat suitability criteria; i.e. professional judgement, utilization, and preference.<br>• Can be used in IFIM, BBM etc<br>• Lacks to consider cover condition | Readily available data is very few. Need survey during the study period | Recommended for high fish potential rivers; especially habitat for migratory fishes in Lake-wetland-river systems | USA; (Wang et al., 2018) |
| | The EVHA (evaluation of habitat) methodology | • a Windows package, Ginot (1995), AGIRE (a multipurpose water GIS) and the method used by ENSAT Toulouse all used similar physical microhabitat simulation | Readily available data is very few. Need survey during the study period | Recommended for high fish potential rivers; especially habitat for migratory fishes | France; (Ginot, 1995) |
| | CASIMIR (Computer Aided Simulation Model for Instream flow Requirements) | • a multi-variate fuzzy approach<br>• applied in regulated streams; hydropower impacts | » | Recommended for regulated rivers | Germany; (Noack et al., 2013) |
| | RCHARC (Riverine Community Habitat Assessment and Restoration Concept) | • hydraulic and physical habitat technique<br>• Used for highly regulated rivers | » | Recommended for highly regulated rivers | USA; (Dunbar et al., 1997) |
| | HEP/HSI 'Habitat Evaluation Procedures'/ 'Habitat suitability indices' | • used to document the quality and quantity of available habitat for selected wildlife species | » | Recommended to target species in rivers | USA; (Burgman et al., 2001) |
| | AVDEPTH habitat model | • To develop relationship between discharge and available habitat | » | Recommended to combine with elements of holistic methodology for application | USA; (Islam, 2010) |

- **Phase 4:** Ecosystem Type Classification. Although no two rivers are exactly the same, systems that share physical features, and or occur within similar ecoregions and or contain similar animals may generally respond to flow alterations in a similar manner. This theory is the basis for the importance of characterizing the ecosystem type being considered for E-flow assessments in an effort to assist with future assessments.
- **Phase 5:** Flow Alterations - here alterations in flows from baseline or current flows are modeled and described. These descriptions are then used in further phases of where the socio-ecological consequences of these altered flows can be determined.
- **Phase 6:** Flow-Ecological-Ecosystem Services Linkages. The importance of understanding what the consequences of altered flows will be, initially requires an understanding of the flow-ecological relationships for ecosystem protection considerations, and flow-ecosystem service relationships to describe social consequences of altered flows. *This phase usually forms an important part of holistic E-flow assessment methods.*
- Phase 7: E-Flows Setting and Monitoring - in this phase the flows required to maintain the socio-ecological system in the desired condition established in the Framework is detailed for implementation. Within these E-flow requirements many uncertainties associated with the availability of evidence used in the assessment, the understanding of the flow-ecology and flow-ecosystem service relationships and analyses procedures used can be addressed through the establishment of a monitoring program. Monitoring data is used to test these hypotheses which drives the adaptive management process.

## 4. Consideration of environmental flows in Ethiopia

### *4.1. Environmental flow research in Ethiopia*

Research endeavors on environmental flows in Ethiopia are few (Reitberger and McCartney, 2011). There are, however,

**Table 5**
Summary of holistic EFA methodologies (adopted from different literatures). Each EFA method is evaluated and recommended for Ethiopia based on data availability and executability. »-the same as above.

| Approach | Definition/Type | Usage and drawback | Recommendation for Ethiopia | | Country and Reference |
|---|---|---|---|---|---|
| | | | Data availability | Executability | |
| Holistic approach | Key flow events for range of ecosystem components identified. flow-ecology-geomorphology-social relationships modeled | • a new and growing direction<br>• advice on flows for maintenance of the whole ecosystem<br>• Best approach! | Data is scarce for this type of eFlow assessment. Need costly survey during a study period. Need also professionals of different discipline | There should be established monitoring stations for future application | |
| | BBM (building block methodology) | • The BBM depends on available knowledge and expert opinion<br>• a prescriptive approach, designed to construct a flow regime for maintaining a river in a predetermined condition;<br>• Building blocks being Maintenance and drought base- and high flows<br>• needs close communication liaison among experts | Flow data is available for major rivers. Lower order rivers need modeling and regionalization. Getting highly experienced professionals in different discipline is a problem | Recommended in data poor catchments from design to operation of large dams in Ethiopia | South Africa; (King and Louw, 1998) |
| | IFIM (Instream Flow Incremental Method) | • the most popular model for simulating the effect of regulated streamflow on fish habitat.<br>• Composed of components which simulate water temperature, water quality, and physical habitat.<br>• The physical habitat component (PHABSIM) is frequently used; and so, confused the IFIM and PHABSIM<br>• PHABSIM lacks considering cover | Time series Fish data is scarce. Other issues the same with previous method. | Recommended for high fish potential rivers; especially habitat for migratory fishes in Lake-wetland-river systems | USA, (Bovee, 1982) |
| | DRIFT (Downstream Response to Imposed Flow Transformation) | • A structured process for combining data and knowledge from all the disciplines to produce flow-related Scenarios (scenario-based approach).<br>• Four modules: biophysical module, socio-economic module, scenarios module and economic module<br>• lists compensation and mitigation costs<br>• Relevant for subsistence users | Need extensive socio-economic data collection and rigorous discussion. Getting highly professionals is a problem in acquiring data/ information | Recommended for cases where subsistence downstream users are high! | South Africa; (King et al., 2003) Lesotho; (Arthington et al., 2003) |
| | ELOHA (Ecological Limits of Hydrological Alteration) | • A synthesis of a number of existing hydrologic techniques and environmental flow methods<br>• Establishes flow-ecology-societal preference relationships to decide IFR<br>• can be used both to guide basic research in hydro-ecology and to further implementation of more comprehensive environmental flow management of freshwater sustainability on a global scale | Need long-term ecological and livelihood data. Data scarce and need extensive data collection during the study period. | Recommended for large scale projects design works and eFlow research in Ethiopia | Global, (Poff et al., 2010) |
| | Savanah processes or Expert Panel Assessment Method (EPAM) approach | • Experts decide amount of releases from storage through workshop, and then a panel of experts assess the appropriateness of the flow<br>• depends on the quality of existing information and the experience of Panel members | Getting highly professionals is a problem in acquiring data/ information | Recommended for highly regulated river basins of Ethiopia; | USA, Georgia; (Warner, 2018) |

ecohydrological studies that can be linked to environmental flow research. Based on the systematic review we did, there are about 52 peer-reviewed articles identified that focused on environmental flow in Ethiopia; the first being in 2007 and the highest (8) being in 2021 (Fig. 3). Among the 12 basins of Ethiopia, most of the papers (44%) are from the Abbay (upper Blue Nile) basin, 19% focused about the whole country, 15% Awash basin, 4% Tekeze basin, 4% Baro-Akobo basin, 4% Gibe basin, and 2% Genale basin. The rest have no studies or the practice of environmental flows (Supplemental material, Table S1).

Based on the literatures reviewed, the environmental flow research in Ethiopia had covered issues connected with water resources planning/allocation, development projects design, environmental flow requirement quantification of river basins, land use change impacts on low flow, climate change impacts on both low flow and high flow, landscape planning, watershed management and general water policy (supplemental material, Table S1). The methods applied for environmental flow requirement quantifications are reviewed and among the 52 peer-reviewed papers 77% applied **Hydrological** methods like Q95 (95% exceedance probability flow), percentage of mean annual flow (%MAF)/Tennant method, Global environmental flow calculator and Desktop reserve model; 4% applied **Habitat rating** methods like PHABSIM; and 2% used expert panels or applied **Holistic** methods (supplemental material, Table S1). The remaining 17% were general evaluations mentioning the importance of environmental flow consideration in water resources allocation (Fig. 4).

#### 4.1.1. A study on environmental flow requirement of abbay river between Chara-Chara weir and the Tiss-Issat fall using the desktop reserve model (DRM)

The Desktop Reserve Model (DRM) was used to determine both high and low flow requirements in the reach containing the 'Tiss-Issat' falls below Chara-Chara weir of Abbay river which provided a preliminary estimate of environmental flow requirements in terms of flow indices to maintain the basic ecological functioning in this reach (McCartney et al., 2009, Shiferraw and Mccartney, 2008). However, to ensure proper management, much greater understanding of the relationships between flow and the ecological condition of the river ecosystem is needed. The results indicate that an average annual allocation of 22% of the mean annual flow should be released as an environmental flow (Shiferraw and Mccartney, 2008).

#### 4.1.2. A study on environmental flow requirement of omo-gibe using Indicators of Hydrologic Alteration (IHA) and the global environmental flow calculator

The study used hydrologic EFA tools such as Indicators of Hydrologic Alteration (IHA) and Global environmental flow calculator (GEFC) to understand the environmental flow indicators from the point of view of climate change impacts (Tesfaye et al., 2020). Effect on ecosystems based on different flow regimes; flow magnitude, frequency, duration, timing, and rate of water condition changes are conferred. The FDC shift approach (GEFC software) recommended to keep the basic ecosystem functions by maintaining "slightly modified to natural habitats" along rivers, where the EFR should be 48–70.5% of mean annual runoff (MAR) in the outlet. It has found the "critically modified class" (ecosystem status below "slightly modified" condition) to be 7.6–12.1% of MAR. Besides, this study using IHA reveals large floods which alter the river and its floodplain's biological and physical structure had occurred in 1994/95 and 2006. And, predictions using Global climate models-climate scenarios depicted the occurrence of large floods seven times for RCP4.5 scenario and three times for RCP8.5 scenario till 2100. This study concluded the importance of understanding the flow variabilities and the necessity of environmental flow for sustaining the biodiversity and maintaining the goods and services that rivers supply.

#### 4.1.3. Research focused on ecohydrological issues in Ethiopia

A review of ecohydrology studies in Ethiopia was compiled by Zalewski et al. (2010) from papers presented at the International Symposium "Ecohydrology for sustainable water ecosystems and society in Ethiopia". Zalewski et al. (2010) included studies in Lake Tana sub-basin, such as: the review of the ecohydrological status of Lake Tana by Ligdi et al. (2010) and is followed by the paper on improving management of lake shoreline and wetlands by Wondie (2010). A recent study in the Lake Tana sub-basin also tried to study the historical water quality dynamics in the lake (Goshu et al., 2020), and indicated that construction of large dams and large-scale irrigation schemes failed to meet environmental and social standards (Annys, 2020), which can serve as information for environmental water requirement studies. It is recommended that the adoption of the European experience in upgrading ecosystem services

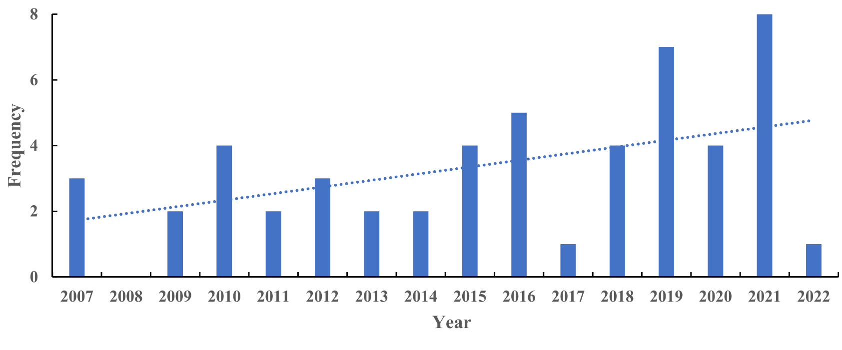


**Fig. 3.** The number of peer-reviewed "environmental flow" papers in Ethiopia; the first in 2007.

might be helpful for acceleration of restoration of hydrological cycle and sustainability based on the ecohydrology concept in most of Ethiopian lakes and river basins (Zalewski et al., 2010).

### 4.2. Environmental flow application on water resources development projects in Ethiopia

#### 4.2.1. Environmental flow assessment report of three dam projects in Lake Tana basin; koga, Ribb and Megech irrigation projects

An environmental flow assessment was done as part of the Koga project (Macdonald, 2004b; Macdonald, 2004a). Data on Koga River flow during the dry and wet season were analyzed and rainfall data from Bahir Dar and Merawi towns stations were compared. Flow releases were decided based on environmental flow assessment using the hydrological data; specifically, the Q95 method was applied. The Q95 method is based on the 95% exceedance value on a seasonal flow duration curve (FDC); where FDCs display the relationship between discharge and the percentage of time that it is equaled or exceeded (King et al., 2000). Based on this method, environmental flow requirement as flow releases was decided at the 95% flow for Koga River downstream of the dam (Fig. 5, Tables 6 and 7).

The same Q95 approach was applied in the Ribb and Megech dam projects. From an ecological perspective, this type of methodology does not adequately address the dynamic and variable nature of the hydrological regime (Abebe et al., 2007). Moreover, the long-term effects of maintaining the minimum flows are rarely the same as the naturally occurring infrequent, short-term effects reflected by instantaneous events in the historic record (King et al., 2000). So, this Q95 method is not adequate or reliable unless it is cross checked with other methodologies which can include more parameters than historical hydrologic data. Further, holistic ecosystem approach studies need to be considered.

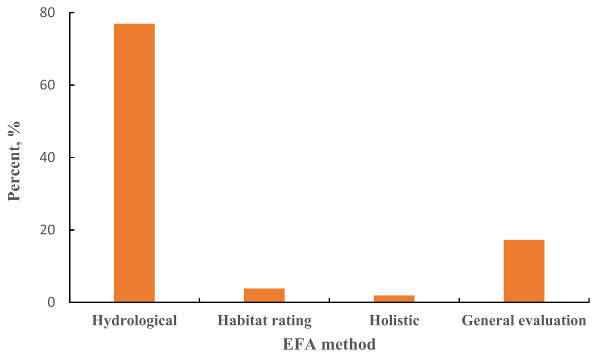


**Fig. 4.** Environmental flow assessment (EFA) methodologies applied in Ethiopia since 2007. A few eflow research outputs in Ethiopia are mentioned in the following sections as case examples.

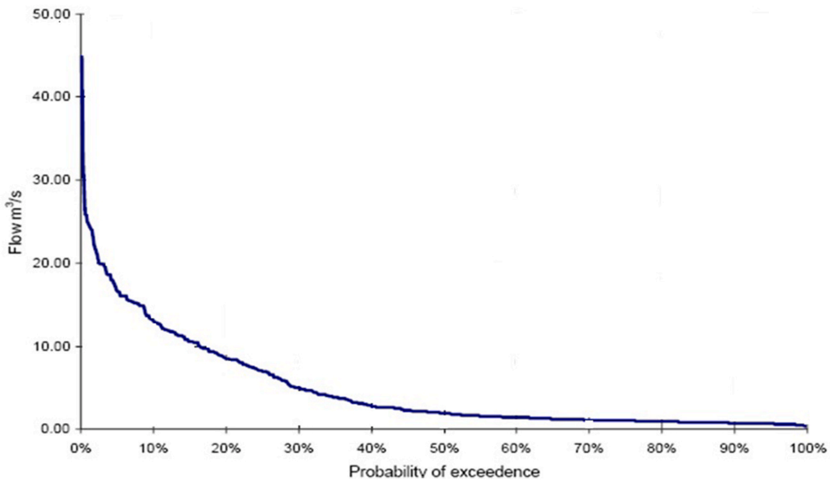


**Fig. 5.** Koga River monthly flow duration curve (source: Macdonald (2004a)). Note. The 95% flow value is the environmental flow requirement decided for Koga river.

**Table 6**
Downstream flow releases from Koga dam. Note. The Q95 flow values are meant to be environmental flow release rates.

| Month | Q95 ($m^3$/s) | Releases volume ($m^3 10^6$) |
|---|---|---|
| January | 0.77 | 1.07 |
| February | 0.53 | 0.97 |
| March | 0.48 | 0.80 |
| April | 0.38 | 0.67 |
| May | 0.50 | 0.80 |
| June | 1.75 | – |
| July | 8.85 | – |
| August | 16.45 | – |
| September | 10.20 | – |
| October | 2.37 | 2.68 |
| November | 1.08 | 1.55 |
| December | 0.95 | 0.80 |

(Source: Macdonald (2004b)).

**Table 7**
Monthly Compensation Flows and Reservoir Levels of Koga dam. Note: The compensation flow is the volume of environmental flow calculated from the Q95 flow values.

| Month | Compensation Release | | Reservoir Level (Middle of month) (m) |
|---|---|---|---|
| | Volume ($m^3 10^6$) | Flow (m 3/s) | |
| October | 2.68 | 1.00 | 2014.50 |
| November | 1.56 | 0.6 | 2014.45 |
| December | 0.8 | 0.3 | 2014.47 |
| January | 1.07 | 0.4 | 2014.26 |
| February | 0.97 | 0.4 | 2013.35 |
| March | 0.80 | 0.3 | 2011.76 |
| April | 0.67 | 0.25 | 2009.48 |
| May | 0.80 | 0.3 | 2006.53 |

(Source: Macdonald (2006)).

### *4.3. Water resources management policy and environmental flow in Ethiopia*

The Ministry of Water Resources has formulated the Federal Water Resources Policy for promoting a comprehensive and integrated water resource management (MOWR, 1999). The main aim of the Water Resources Policy is to increase national efforts towards optimum and sustainable utilization of the available water resources for socio-economic development. The policy emphasizes the establishment and institutionalizing of environment conservation and protection requirements as integral parts of water resources planning and project development. The general water resources management policies of Ethiopia as outlined in the policy document mentioned two issues directly linked with environmental flow which give emphasis to conservation and protection of the water resources. First, recognize that water resources development, utilization, protection and conservation go hand in hand and ensure that water supply and sanitation, irrigation and drainage as well as hydraulic structures, watershed management and related activities are integrated and addressed in unison. Second, recognize water as a scarce and vital socio-economic resource and to manage water resources on strategic planning basis with long term visions and sustainable objectives (MOWR, 1999). Besides, cross-cutting issues part of the water resources policy included detail water allocation issues including water for the environment. The cross-cutting policies on water allocation and apportionment; stated as: recognize that the basic minimum requirement, as the reserve (basic human and livestock needs, as well as environment reserve) has the highest priority in any water allocation plan (MOWR, 2001).

In addition, the Federal Government of Ethiopia has formulated and approved the Environmental Policy of Ethiopia (EPE) in 1997 (Kefauver, 2011). The key objective of the policy is to update and suggest corrective measures to remove deficiencies of the previous policies for the environmental protection and conservation. This policy is integrated with the long-term Agricultural Development Led Industrialization, and other important Sectoral policies. The thrust of EPE is to achieve sustainable development in agriculture, water resources, industrial and infrastructure sectors; and, as a result, improve and enhance the quality of life of its citizen. The policy contains Sectoral and cross-Sectoral policies and various guidelines for its implementation. Moreover, the national policy for fisheries has two main objectives; first, to encourage fisheries development and protection of biomass and the second objective stresses on the protection and maintenance of fish biomass against over-fishing, pollution, poaching and introduction of exotic species (MOARD, 2002). The National Biodiversity Strategy and Action Plan (NBSAP) of Ethiopia is also a useful document providing analyses of the state of biodiversity and the environment at large over the past decades, the root causes of the biodiversity loss and the adverse consequences against social and economic developments (Ababa, 2005). These consequences are presented both in terms of impacts on ecosystems and vulnerability of human populations to droughts, floods, diseases, pests, etc. The NBSAP brings out the multidimensional challenges and opportunities that biodiversity conservation provides not only to citizens but to the world community at large.

The above policies and strategies gave emphasis on water protection which can be practical through environmental flows.

## 5. Discussion

### *5.1. E-flow benefits and opportunities*

International experiences showed that maintaining environmental flow in rivers has several benefits to aquatic ecosystems and the rendering of ecosystem services (Poff et al., 2017; Arthington, 2012; Watts et al., 2009). Some of the benefits are flood management, maintaining drought flow, and restoration of water bodies. Some of the opportunities to implement an environmental flow framework in Ethiopia include:

- The Water Resources Policy of Ethiopia has acknowledged the need for an ecological reserve
- There are past research outputs on environmental flows, focusing on some methodologies of EFA and ecohydrological studies
- The country has already conducted EFAs in water resources development projects, especially World Bank and African Development Bank (AfDB) financed water resources development projects

### *5.2. The challenges to the application of environmental flow*

The many challenges existing globally complicates the solutions to water shortage; construction of large dams and large-scale irrigation schemes, although made climate-resilient for the agricultural and energy sectors, have failed to meet environmental and social standards (Annys, 2020; Amede et al., 2011). Monitoring and evaluation of environmental flow is also rare (Watts et al., 2009). Safeguarding ecosystems is threatened by agricultural expansion to alleviate poverty and increase food security (De Fraiture et al., 2007). There is also an increasing risk of overlooking the complexity of the natural system and applying simple environmental flow recommendations to solve water resource problems that will ultimately contribute to further deprivation of river ecosystems (Arthington et al., 2006). Kansal et al. (2014) mentioned that water scarcity is deeply rooted in Ethiopia because of a poor legal framework for strong institutional setup and consequent inefficient use of water resources.

Environmental considerations, regarding environmental flows, of water resources development projects were reviewed in different parts of Ethiopia including projects around Lake Tana basin which are basically hydrologic data based. The Q95 method is used in deciding the monthly flow releases to maintain the downstream river ecology considering only maintenance requirements for normal years, but there is no consideration for drought period requirements. There is also no mention of higher flow requirements. Often flood flows are important for the maintenance of downstream floodplain ecosystems. A full holistic ecosystem approach analysis of flow requirements would undoubtedly have identified a range of flow requirements. As far as possible these should have been linked to the livelihood needs of downstream communities in terms of their natural resource requirements. This is the drawback of the methodology used (Q95) to check whether the flow releases met environmental requirements although this could be sufficient for water resources planning at reconnaissance stage. In summary, the successful application of EFAs in Ethiopia is still limited. Some of the key challenges of water allocation for environmental reserve based on environmental flow assessment include; adapted from Reitberger and McCartney (2011):

- Lack of capacity in terms of human, finance and institution
- Lack of both hydrometric and ecological data; which also lack emphasis by responsible water sectors to establish monitoring stations and establish databases
- Inadequate conceptualization of causes of changes in flow regimes to the multifaceted environmental and social relations
- The need for eflow research throughout the country on different ecosystems
- Lack of adaptation and development of EFA methods and constraints to the application or implementation of EFAs

### *5.3. Research issues*

Based on the prevailing ecological and societal problems linked to aquatic resources, rigorous research is needed in the area of ecohydrology of environmental flows to advise policy makers; such as:

- Instream flow requirement of fish species that require flow like the migratory fishes of Lake Tana, riparian vegetation and other biota like aquatic macrophytes and macro-invertebrates in the tropical highland rivers of Ethiopia
- Establishing ecological monitoring stations on rivers and build ecological knowledge in relation to environmental flow assessment/flow regime change
- Research based EFA methodology adaptation (hydrological to holistic at different scales of water resources planning) elsewhere in the world or development based on local knowledge

### *5.4. Policy issues*

The water resources development policy of Ethiopia at national and regional should be reviewed from an IWRM perspective. The environmental protection authority recommended to develop a detail statute of the EIA proclamation and enact environmental flow assessment methodologies at different scales of water works for safeguarding aquatic and riparian ecosystems. It is advised to implement environmental flows because they are rarely implemented even in already planned projects. A scheme/institution of monitoring environmental flows is recommended for water bodies being harnessed in already operational water abstraction projects. This will help to understand the ecological status of water bodies under development and seek for restoration in cases where degradation is severe beyond prior expectations.

## Ethical statement

The research was done according to ethical standards.

## Funding body

The review article was financed by Amhara design and supervision works enterprise as part of a PhD study.

## Declaration of competing interest

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

## Data availability

I have attached my data as supplementary material

## Acknowledgements:

The Authors acknowledge MoWR of Ethiopia and the project consultant firm Mott McDonalds for providing Koga irrigation dam project's environmental flow assessment design documents; especially the hydrological study and ESIA. We are grateful also for consultants at Ribb and Megech for providing access to the hard copies of the design documents and take notes of the ecological flow release plans.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envdev.2022.100758.

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