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Towards Good E-Flows Practices in the Small-Scale Hydropower Sector in Uganda

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Stakeholders of the small-scale (<50 MW generation capacity) hydropower sector in Uganda recognise the importance of sustainable development of the resources that have social and ecological importance. Uganda is experiencing a boom in hydropower projects resulting in over generation of electricity and its exportation to neighbouring nations. Limited policies are currently available in Uganda to direct the sustainable development of this sector. Environmental flows (e-flows) practices established for the Nile Basin region and international good e-flows practices can contribute to sustainable management of hydropower developments in Uganda. The paper defines and explains e-flows, identifies water resource attributes of importance for e-flows determination associated with hydropower and threat associated with this activity in Uganda, and provides good e-flows determination and management practices based on regional and international information. The determination and management of e-flows in the hydropower sector in Uganda is largely dependent on the availability of and quality of hydrology, hydraulic and flow-ecosystem and flow-ecosystem service relationship information. This review of good-practice e-flows practice for the small hydropower sector in Uganda provides guidance to support multiple stakeholders of water resources in Uganda for a better future for all of its vulnerable communities and the environments they depend on.

Keywords: hydropower, environmental flows, river ecology, Uganda, sustainability, water resources management and development

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INTRODUCTION

Hydropower is the primary source of electricity generation in Uganda. It accounts for 78% of the total installed capacity of 1182.2 MW, generating 3330 GWh of electricity (ERA, 2019). Large-scale hydropower has an installed capacity of 813 MW, 68% of total installed capacity, characterized by a number of stations on the Victoria Nile, including the Bujagali (250 MW), Kiira (200 MW), Nalubaale (180 MW), the Isimba Falls (180 MW) which became operational in early 2019. Smaller hydropower developments (<50 MW in capacity) currently produce a combined 176 MW, which totals 22% of Uganda's installed power generation capacity (sensu ERA, 2019). The small-scale hydropower plant sector in the Africa is developing rapidly with numerous Independent Power Producers (IPPs) developing plants in more than half of the countries in Africa (Moner-Girona et al., 2016; O'Brien et al., In press). These plants are considered to have better cost-benefit ratios than large hydropower dams and fossil fuel power generation plants due to their relatively low cost of installation, robustness and longevity, and importantly the potential to access remote communities who have a high demand for power (Pang et al., 2015; O'Brien et al., In press). This sector is expected to grow considerably in the near future (O'Brien et al., In press). Hydropower plants almost inevitably have pernicious impacts on the wellbeing of river ecosystems and the livelihoods of people using their ecosystem services (McCarthy et al., 2008; Liechti et al., 2015; Lynch et al., 2019). These impacts could include disruptions in the connectivity of river habitats, and/or changes in the volume, timing, duration and frequency of flows and indirect impacts on other environmental variables such as water quality. While the management of the flows of water in rivers is well established globally, in Africa developments from South Africa in particular has dominated sustainable water resources management (King and Pienaar, 2011; Nile Basin Initiative, 2016; GET FiT, 2018; O'Brien et al., In press). African nations including Kenya and Tanzania have directly included South African water resource management policies into their legislation, and the Nile Basin Initiative has included components of South African policies as good practice into their water resource management (Nile Basin Initiative, 2016; O'Brien et al., 2018; Dickens et al., 2019; O'Brien et al., In press). In Uganda water resource developers, conservationists, scientists and regulators have limited guidance on the local effect of altered flows associated with hydropower development. While the Nile Basin Initiative (NBI) provides regional guidance on e-flows and how to manage multiple stressors (Nile Basin Initiative, 2016), it does not provide good practice guidance that is specific to the water resources in Uganda to allow these Ugandan stakeholders to manage the effects of altered flows associated with small-scale hydropower development. Sustainable water resource management that considers e-flows is essential to ensure that development in Uganda does not negatively impact on vulnerable ecosystems and the human communities who depend on these systems for their livelihoods.

Management of the e-flows of a river is recognized as a possible way of mitigating the impacts of hydropower plants, and indeed understanding the e-flows of all rivers has become a corner-stone of water resources management (Horne et al., 2017). Since the 1990s e-flows are generally now included not only in water resources planning but also as part of the mitigation of individual river developments including hydropower schemes (Poff and Zimmerman, 2010; Pahl-Wostl et al., 2013; Poff and Matthews, 2013; O'Brien et al., 2018). Environmental flows also now form an essential part of the indicator method for the Sustainable Development Goal SDG 6.4.2 indicator of the degree of "water stress" being exerted on a water resource (Vanham et al., 2018; Dickens et al., 2019), and thus should be on the agenda of all water-resource managers.

It was only after the 1990s that the effects of altered flows in the environment began to be considered in a dedicated manner (Pahl-Wostl et al., 2013; Horne et al., 2017) This transpired after extensive dam construction in particular led to large scale obstruction of free-flowing rivers and a noticeable loss of ecosystem services, including fish stock in particular and natural habitats and biodiversity (Poff and Matthews, 2013). The prevailing question became to understand the water flow-ecology relationships, the human impacts on the delivery of ecosystem services and above all the question; "how much water does a river need to sustain itself and the livelihoods of people who depend on them" (Pahl-Wostl et al., 2013).

Over subsequent decades, the concept of e-flows has evolved to encompass river flow variability, river connectivity (longitudinal and lateral), ecosystem services and human wellbeing and a suite of methods have been developed and applied globally to quantify various components of e-flows (Tharme, 2003; Petts, 2009; Adams, 2014). Today various e-flows policies (King and Pienaar, 2011; Nile Basin Initiative, 2016), frameworks and determination methods (Poff et al., 2010; Nile Basin Initiative, 2016) are available to contribute to the development of "good" e-flows practices for Uganda.

Implementing a strategy to provide for e-flows is essential for hydropower development primarily because e-flows provide a boundary for development, providing a measure of river flow that should not be lost as it is needed to sustain the ecosystem and the people who rely on that ecosystem, and also because implementation of e-flows provides a way to mitigate the impact of the hydropower development on a river system. This paper aims to review and recommend e-flows determination and management practices applicable to the small-scale hydropower sector in Uganda and the sustainable management of water resources in Uganda across multiple spatial scales. The paper defines and explains e-flows, identifies water resources of importance for e-flows determination associated with hydropower development in Uganda, and recommends appropriate e-flows determination and management practices based on regional information.

Water Resources in Uganda

Uganda is a landlocked nation of 241550.7 km^2, located within the equatorial regional of Africa (**Figure 1**). The nation receives an annual average rainfall of 1180 mm primarily during two rain seasons (Nsubuga et al., 2014). Uganda is located within the White Nile Basin between Lake Victoria and the Sudd Wetland of the Nile basin and has 16% of its area covered by lakes or wetlands. This nation has abundant water resources and is ideally located within a region of Africa with a high demand for electricity and abundant potential for hydropower. The landscape of Uganda consists of a high altitude (1,050 m.a.s.l.) plain within the rift valley of Africa, with mountains in the east (Elgon Mountain 4,321 m.a.s.l) and in particular along the west of the country (Rwenzori and Virunga mountains, maximum 5,119 m.a.s.l. The average flow (discharge in m^3/s) from the major lakes into the Nile Rivers in Uganda has been variable, particularly when comparing the "dry period" of 1905–1961 with average flows of 840 m^3/s and the wet period from 1962 to 2008 with average flows of > 1200 m^3/s (Nsubuga et al., 2014). In Uganda the population has increased from 12 Million people in 1980 to 44 Million in 2008 (Nsubuga et al., 2014). All of these people depend on the water resources of the nation and the services it provides. Sustainable development and management of these resources for the biodiversity and livelihoods of vulnerable Ugandans is imperative.

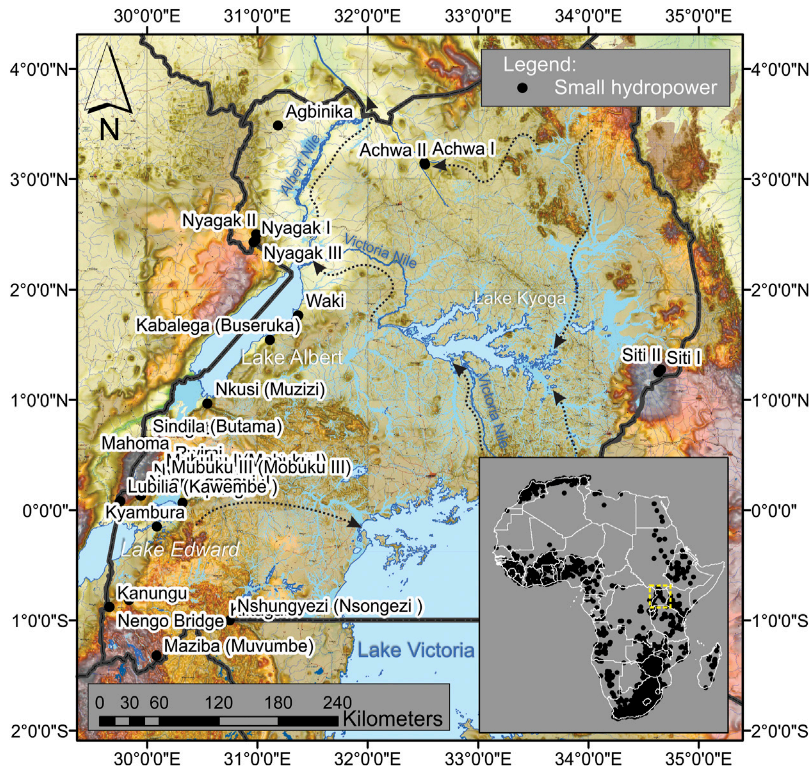

FIGURE 1 | Map of Uganda, with lakes and rivers and direction of flow (dotted lines). Small (<50 MW capacity) hydropower plants included.

Small-Scale Hydropower in Uganda

There are currently > 29 small-scaled hydropower plants in operation or being built in Uganda (**Table 1**; **Figure 1**). With the new developments power production of small plants will increase production in Uganda to at least 332 MW (34% of hydropower generation in Uganda, (**Table 1**). Small-scale hydropower stations are concentrated in the Rwenzori Mountains and Mount Elgon, and also on less turbulent reaches of river in lowland, lower rainfall regions, with varying ecology and land use systems compared to the large-scale stations on the Victoria Nile. Many of the developments (n > 14) have been commissioned through the GET FiT (Global Energy Transfer Feed-in Tariff scheme) program. Launched in 2013 with the intention to leverage private investment for renewable energy generation in Uganda, it has been developed by the Government of Uganda, the Electricity Regulatory Agency (ERA) and KfW, receiving funding from international donors. The program includes 20 small-scale renewable energy generation projects, including a number of small-scale hydropower stations, as well as solar and bagasse (**Table 1**). As of 2020, 139 MW of installed capacity is in operation, generating > 271 GWh, 7% of total electricity supplied to Uganda, including fourteen small-scale hydropower stations (GET FiT, 2018).

In recent years Uganda has experienced periods of electricity over-capacity, allowing export to neighboring Tanzania, Kenya, Rwanda and the Democratic Republic of Congo (ERA, 2019). Peak electricity demand reached 644 MW in 2018 (ERA, 2018), with over-capacity increasing since the Isimba Falls (180 MW) became operational in early 2019. Uganda faces a period of further over capacity in light of the 600 MW Karuma and the 600 MW Ayago stations presently under construction on the Victoria Nile, due to be operational by 2020 and 2026, respectively; the Achwa 1 and 3 stations on the River Achwa (41 and 10 MW); the Muzizi station (48 MW) near the south-east shores of Albert Lake; and the 157 MW GET FiT renewable energy portfolio when fully operational. With slow to moderate growth in industrial demand and slow increase in rural household connections, this in turn may mute prospects for further deployment of private sector-developed smaller scale hydropower projects in the near to mid-term. However, experience from other African countries where electricity became available (e.g., South Africa had 1.3 million new connections over a three year period from 2006–9) has shown very rapid uptake, within the context of a conducive institutional, economic and operational environment (RoSA, 2011).

Improving electricity transmission and distribution would allow greater levels of domestic consumption in Uganda, especially considering that only an estimated 22% of the population and 14% of households have access to electricity (World Bank, 2019). Electricity consumption in Uganda is amongst the lowest levels in the world, half the average of Sub-Saharan African countries (Kamese, 2004). Biomass is a critical source of energy for the majority of the population,

TABLE 1 | Summary of the small (<50 MW capacity) hydroelectric power plants in Uganda with developer, capacity, commissioning date and involvement as a GET FiT project (GET FiT, 2018).

Name	River	Latitude	Longitude	Project special purpose vehicles/Developer	Capacity (MW)	Commission date	GET FiT
Achwa I	Achwa	3.148056	32.514167	Berkeley energy	10.0	WIP	NO
Achwa II	Achwa	3.135000	32.520833	Berkeley energy	41.0	2019	NO
Agbinika	Kochi	3.485416	31.185417	Uganda government	20.0	WIP	NO
Bugoye (mobuku II)	Mubuku	0.309038	30.102083	Bugoye hydro limited	13.0	2012	NO
Kabalega (buseruka)	Wambabya	1.545485	31.111478	Hydromax limited	9.0	2013	NO
Kanungu	Ishasha	-0.878611	29.657500	Eco-power limited	6.6	2011	NO
Kikagati	Kagera	-1.029090	30.679243	Kikgati power company limited	16.0	WIP	Yes
Lubilia (kawembe)	Lubilia	0.083333	29.754444	Lubilia kawembe hydro ltd	5.4	2018	Yes
Mahoma	Mahoma/ Dura	0.478611	30.273056	Mahoma Uganda limited	2.7	2018	NO
Maziba (muvumbe)	Muvumbe	-1.318750	30.082957	Muvumbe hydro Uganda limited	6.5	2017	Yes
Mpanga	Mpanga	0.067388	30.321557	Africa energy management system	18.0	2011	NO
Mubuku I (mobuku I)	Mubuku	0.318611	30.100000	Tibet hima mining Co. ltd	5.0	1956	NO
Mubuku III (mobuku III)	Mubuku	0.260278	30.149444	Kasese cobalt company limited	9.9	2009	NO
Nengo bridge	Mirera	-0.814583	29.833370	Jacobsen elekro	6.5	WIP	NO
Nkusi (muzizi)	Nkusi	0.966206	30.546295	PA technical services Uganda limited	9.6	2018	Yes
Nshungyezi (Nsongezi)	Kagera	-1.000239	30.745595	Nsongezi power company limited	39.0	WIP	NO
Nyagak I	Nyagak	2.430556	30.963889	-	3.5	2012	NO
Nyagak II	Nyagak	2.500028	30.989583	Public private partnership	5.0	2018	NO
Nyagak III	Nyagak	2.449945	30.981250	-	4.4	WIP	NO
Nyamwamba	Nyamwamba	0.230850	29.985817	Africa EMS Nyamwamba limited	9.2	2018	Yes
Rwimi	Rwimi	0.390055	30.181250	Rwimi EP company limited	5.5	2017	Yes
Siti I	Siti	1.250000	34.636944	Elgon hydro siti (PVT) limited	5.0	2017	Yes
Siti II	Siti	1.276389	34.657778	Elgon hydro siti (PVT) limited	16.5	2016	Yes
Sindila (butama)	Sindila	0.630000	29.978056	Butama hydro-electricity company ltd	5.3	2019	Yes
Waki	Waki	1.766116	31.368750	Hydromax Nkusi ltd	4.8	2018	Yes
Kyambura	Kyambura	-0.148889	30.088611	Zibra limited	7.6	2019	Yes
Ndugutu	Ndugutu	0.615556	29.979444	Ndugutu power company Uganda limited	5.9	2019	Yes
Nyamagasani I	Nyamagasani	0.137778	29.934722	Rwenzori hydro private limited	15.0	WIP	Yes
Nyamagasani II	Nyamagasani	0.130000	29.942500	Nyamagasani 2 hydroelectric power project limited	6.0	WIP	Yes

particularly in rural areas, accounting for an estimated 90% of Uganda requirements (UNDP, 2014).

Effects of Hydropower Developments and Operation on River Ecosystems

Hydropower plants impact on river ecosystems in numerous ways; mainly through the alteration of the river water and sediment flow regimes, cause water quality impacts, barriers and disturbance to wildlife stressors (Moog, 1993; Rolls and Bond, 2018; O'Brien et al., In press). Generally, small scale hydropower production is unique in that it can be non-consumptive where water is diverted through hydropower generation infrastructure and then returned to the river system (**Figure 2**). When there is no overall impact on river flows, small hydro developments are termed "run of river" which comes together with the connotation that these types of hydropower plants do not cause any negative ecological impacts (Anderson et al., 2015) (**Figure 2**). However, the synergistic impacts related to the formation of barriers, change in erosion dynamics and water quality of the rivers as well as alterations in the timing duration and frequency of flows on daily and seasonal scales must be considered (Anderson et al., 2015; O'Brien et al., In press).

Small-scale hydropower generally can contribute to the following ecosystem issues:

1. Alterations to the natural flow regime (consider **Figure 2**).
   a. Where there is storage as part of the hydropower development, storage dams can buffer natural flow variability, and may provide opportunity for other users of water to withdraw water from the storage and thus reduce volumes (Anderson et al., 2015; Rolls and Bond, 2018).
   b. The configuration of dam/weir and downstream powerhouse/tailrace impacts particularly on the river section below the dam and above the tailrace, which in some situations may become a dewatering zone/reach (**Figure 2B**). Flows in this section tend to fluctuate widely depending on operation of the system, resulting in a highly stressed ecosystem (**Figures 2B,D**). This is particularly exacerbated in Uganda when the power grid receiving power from hydropower facilities experiences failures (trips) and the hydropower plant must immediately cease supplying power. During these occurrences, normal operation of the plant ceases with water being diverted from the headrace, over the weir into

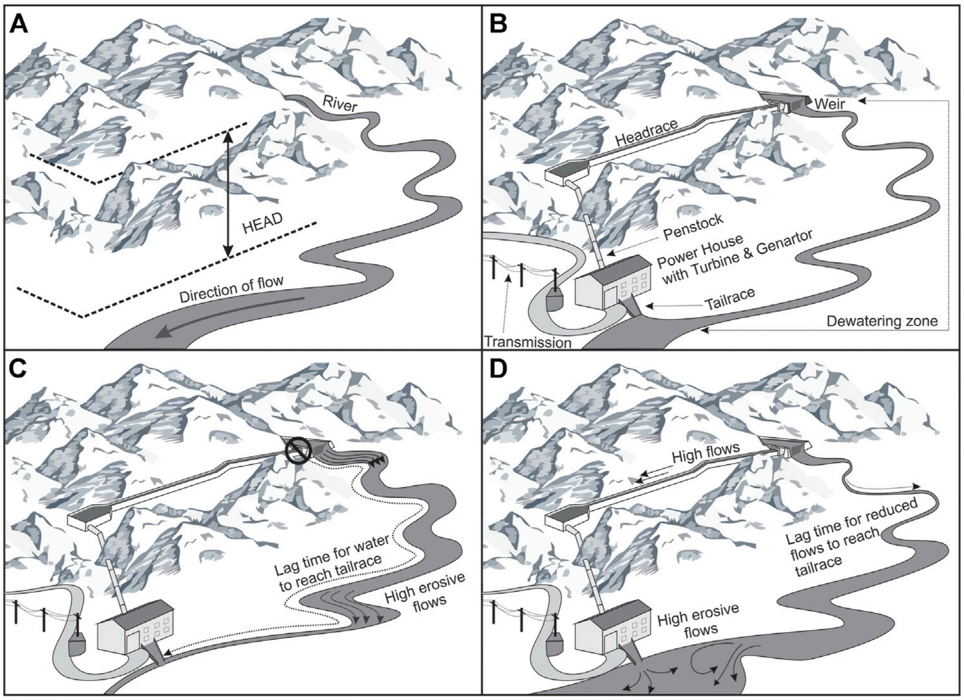

FIGURE 2 | Diagram of a typical small (<50 MW) hydropower installation build on a natural landscape **(A)**. The infrastructure associated with the development is indicated in **(B)** and the effect of rapid flow (volume) alterations on the rivers is demonstrated in Figure **(C,D)**. Rapid flow alterations can be associated with a loss of transmission capacity where the diversion of flows into the headrace of the facility is cut off **(C)**, this results in a decrease (no return) of flows in the river below the tailrace for the duration of the down time. During this period, elevated flows flow over the weir and down the dewatering zone during a lag period until flows reach the tailrace. When power is restored to the grid **(D)** Additional flows in the penstock and headrace are added to flows in the river, and usually elevated to "ram" the grid to energize it. During this period, additional flows are released from the tailrace into the river and the dewatering zone flows are noticeably reduced or cut off until normal operation is resumed **(B)**.

the dewatering zone. During this period flows reduce significantly downstream of the power plant as there is a lag period for the water being diverted from the weir to reach the power plant. An example of this was monitored by the authors on 2–3 October 2018 at the Rwimi plant (**Table 1**), which experiences numerous such transmission restriction events, two of which were observed. During transmission loss events, following the halting of water flow into the headrace, automatic valves in the power house divert water over the weir into the dewatering zone. It took 22 min (**Figure 2C**) for this diversion to reach the powerhouse inundating the dewatering zone. During this lag period, flows below the power house reduced from 4.9 m^3/s (± 0.5 m^3/s) to >1 m^3/s in less than 5 min, which was maintained during a lag period as diverted flows inundated the dewatering zone for 22 min. Flows below the power plant then returned to 4.2 m^3/s and were sustained during the down period for approximately 6 h until power generation resumed. In the power plant when the turbines were activated approximately 6 h after transmission loss (consider that this period is highly variable), the hydropower plant needed to energize the transmission grid, temporarily increasing electricity generation by ramming excess water stored in the penstock, headrace and weir. This resulted in an additional rapid increase in observed flows downstream of the power plant from 4.2 to 7.1 m^3/s that was planned to be maintained from approximately 20 min after which generation would be reduced and maintained. Unfortunately after approximately 15 min of ramming the flows through the power plant to energize the grid another transmission failure occurred. And the flows downstream of the plant again returned to <1 m^3/s. During normal operation flows returned to 4.2 m^3/s. These events were reported to occur consistently (on at least three to five occasions per week) on this single plant at Rwimi (Rwimi EP Company Limited, 2018) (shape of these flows demonstrated graphically in **Figure 3A**). These radical changes in flow will have serious impacts on the ecosystem of the dewatering zone as well as for a distance below the tail-race. It was observed that many invertebrates died in a few minutes, and the local people flocked to the river to pick up stranded fish. Rapid increases in flow do occur in nature, so most river ecosystems are adapted to deal with them. Rapid declines in flow, however, are abnormal and many attributes of ecosystems are unable to retreat in response to the falling water level, often resulting in mass mortalities (Power et al., 1996; McAllister et al., 2001; Anderson et al., 2015; Rolls and Bond, 2018). When this happens on a daily basis, this can

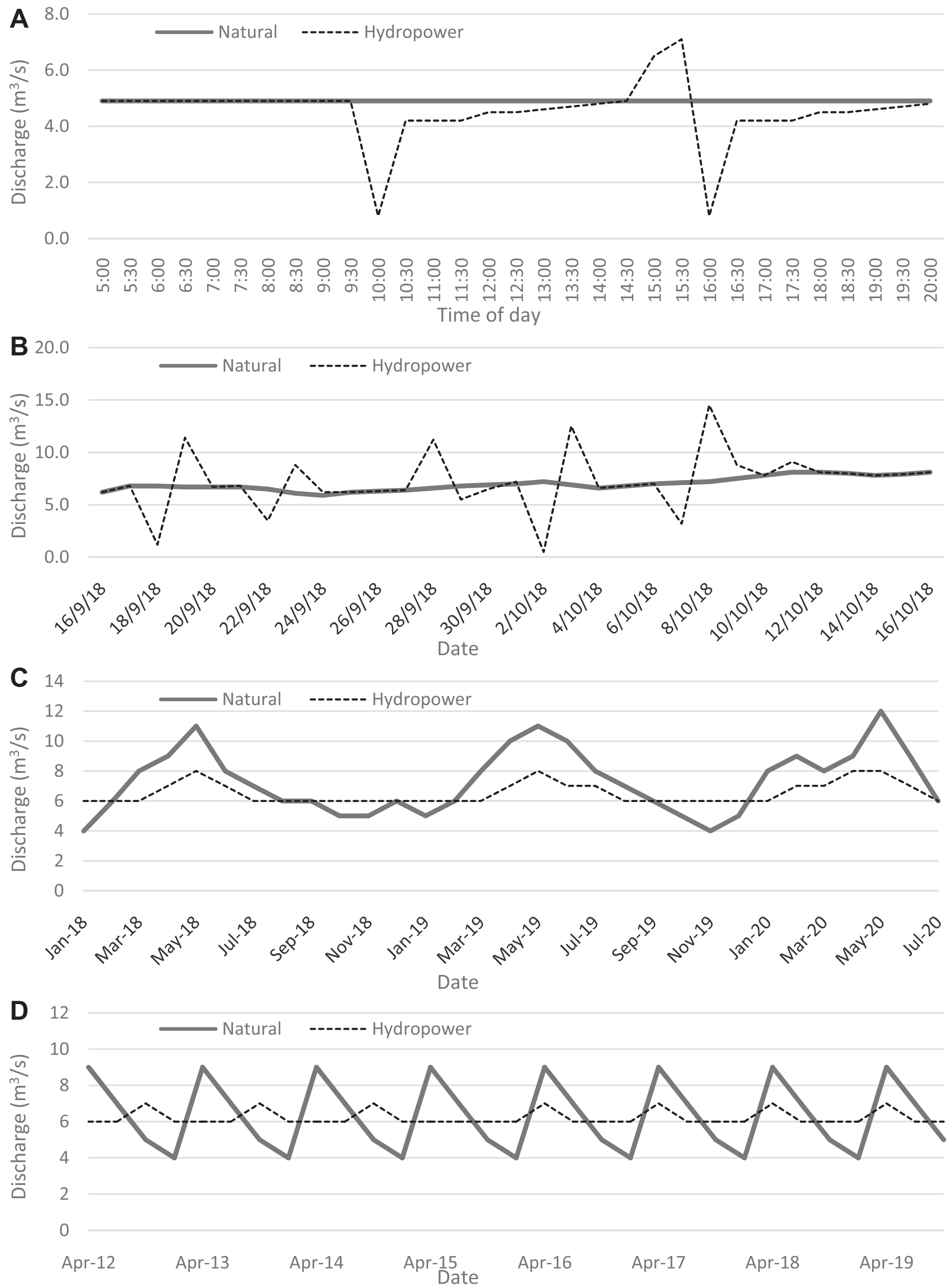

FIGURE 3 | Hourly **(A)**, daily **(B)**, monthly **(C)** and multi-annual **(D)** hydrograph of a river with natural and small-scale hydropower plant flows. Including demonstrations of transmission loss effects **(A)** and associated hydropeaking **(A,B)**, loss of flow variability **(C,D)** with example of reverse hydrograph [**(C)**, April 2012 to Apr 2015].

be devastating to the populations and overall biomass of in particular invertebrates but also fish. During the event observed in the Rwimi River on 2 October 2018, large Cyprinids that preferred deep habitats were forced into shallow pools during the approximately 22 min after the transmission failure event on the Rwimi Power Plant. These fish were harvested by local communities during this vulnerable period.

c. Water releases, either directly from the storage dam or from the tailrace, are generally driven by the need for power generation. Such releases are unlikely to be sympathetic to ecological needs and generally fluctuate rapidly, sometimes on a daily or even hourly basis but also having sustained effects at monthly and multi-annual time-scales (**Figure 3**). **Figure 3** demonstrates the flow scenario observed at the Rwimi Power plant during power transmission outages.

Outflow from below a hydropower plant including hypothetical natural (base) flows and actual hydropower releases to demonstrate the effects of short-term transmission cuts (**Figure 3A**) and associated hydropeaking (**Figures 3A,B**), loss of flow variability (**Figures 3C,D**). Both a constant baseload as well as a peaking power release will have negative impacts on the downstream ecosystem for reasons that will be discussed below. Similar fluctuations may occur where generation alternates on and off in order to provide for fluctuating demand for electricity.

2. The impact of altered flows on the instream and riparian ecosystem.
   a. Change in river morphology; repeated inundation then draining can cause slumping of soil on the river banks, and thus bank erosion (Mcallister et al., 2001; Anderson et al., 2015). Dams and weirs also intercept sediment flows, and can thus lead to scouring of the downstream river and armouring of the habitat. The water can also become less turbid, which will be negative for species evolved to live in turbid waters e.g., clear water exposes them to predators (Anderson et al., 2015).
   b. River connectivity; ecosystems are unique in that they change and develop as the river runs from source to sea, so a mountain stream is a very different ecosystem to a coastal plain river. Constructing a large dam or weir in the path of a river breaks the continuity that many ecosystem functions depend on (Anderson et al., 2015; Zarfl et al., 2015). Key amongst these is that various fauna, particularly fish but also invertebrates, need to migrate upriver in order to complete their life-cycle and also they contribute to ecosystem functioning in both the upstream and downstream portions of the river. Dams and weirs thus can have a substantial impact on ecosystem connectivity. While by-pass structures e.g., fish ladders, can ameliorate these impacts, their benefits are usually only partial (Lynch et al., 2019; O'Brien et al., 2019). Note that many rivers have natural breaks in connectivity e.g., waterfalls or very steep rapids, to which the river ecosystem has evolved. Larger waterfalls may provide a permanent barrier to upstream migration of some species although eels can generally climb these barriers when they are still small. Even the biggest waterfalls do not prevent downstream migration. Smaller waterfalls and rapids may become less of a barrier during flood flows as organisms may be able to scale these obstacles using the still water at the edge.
   c. Signals to biota; altered flows send out confusing signals to biota living downstream, confusing in particular their natural cues to migrate and breed (Lynch et al., 2019). Many species, including both fish and invertebrates, have very specific requirements for increased water flows (e.g., that arrive at the beginning of the wet season) as well as specific water quality (e.g., rising temperatures) to stimulate their need to breed. Regulated flows can thus be detrimental to populations by affecting their ability to complete life-cycles.
   d. Desiccation of the river substrate; following a sudden drop in flow can lead to loss of the periphyton (algae living on the rocks etc.), leading to a loss of primary production and thus a loss of food for the rest of the food chain including people. In addition, death of invertebrates and even fish is commonplace (Anderson et al., 2015).
3. Other impacts of small-scale hydropower plants on biota:
   a. Mechanical damage of turbines that injure and or kill fish and other biota is well documented and should be carefully considered when establishing small-scale hydropower developments, while new turbine designs factor in non-destruction of fish (Charles and Whitney, 2001; Schilt Carl, 2007). Loss of these fauna can affect both ecosystems and the livelihoods of subsistence fishermen.
   b. Disturbance to wildlife impacts are derived from hydropower developments that facilitate water resource development and urbanization of natural areas. The increase of people and their activities along rivers with the maintenance of the hydropower infrastructure results in a disturbance to wildlife where many mobile aquatic (such as fish) and riparian species (such as mammals and aquatic birds) avoid the development area. These impacts are similar to the effect of alien invasive species that compete with and or predate on indigenous animals (Kennard et al., 2005). Indigenous species tend to avoid areas of negative disturbances (Ellender and Weyl, 2014).
   c. Reduced resilience of biota to environmental variability and climate change; the synergist effects of barrier formation, habitat alterations and impacts of activities on the life-cycle ecology of species all affects the resilience of species to natural and anthropogenic changes in environmental variability including climate change. Many aquatic animals that lose resilience have reduced ability to survive droughts and or excessive changes between dry and wet phases of ecosystems (Arias et al., 2014).

Incorporating E-Flows Management for the Hydropower Sector in Uganda

Environmental flows *describe the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, livelihoods, and well-being* (Arthington et al., 2018), a definition that emerges from the Brisbane Declaration (2007). The definition of e-flows spans the twin responsibilities of management, to balance *the use* and *the protection* of the water resource, i.e., it seeks to provide the flows required to maintain sustainable ecosystems and at the same time, the human use derived from the ecosystems to meet livelihoods (Arthington et al., 2018).

Environmental flows exist and can be determined for all riverine, wetland, estuary, lake and groundwater ecosystems, whether the ecosystem is in a natural or altered state (Arthington et al., 2018). Prior to the development of water resources, flow variability is influenced by natural climatic, hydrological and physical ecosystem processes that are considered to represent the "natural" or "historical" flow

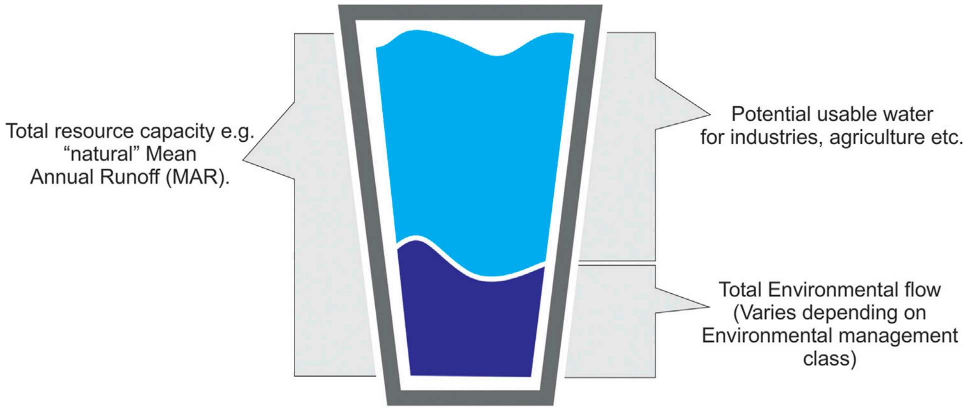

FIGURE 4 | A schematic view showing the total water resource, the e-flows (EF) and the utilizable/allocatable portion (adapted from Dickens, 2018).

regime (Poff et al., 2018). Adoption of e-flows and e-flows management is only important when the development, or use of resources and other anthropogenic activities such as climate change or water pollution, poses a risk as changes in river flow may become excessive and threaten the resource base on which development depends. Indeed, e-flows can be described for all water resources including those in a natural condition, but usually are only characterized and managed when a conflict between the use and protection of water resources threatens the sustainability of the resource (Arthington et al., 2018).

The diagram below (**Figure 4**) offers a simplistic view of the volumes of water required for e-flows (adapted from Dickens et al., 2018). Environmental flows form the foundation for water resource management and in many countries are guaranteed by law. All volumes of water in excess of the e-flows can be considered to be the utilisable or "allocatable" water that resource managers can allocate to hydropower, agriculture, industry or domestic water users. **Figure 4** does not however show an essential component of e-flows, i.e., the timing, frequency and duration of flows designed to represent the natural hydrograph of a river.

An example hydrograph (**Figure 5**) from the Niger River in Mali (Dickens et al., 2018) shows how the duration, timing and frequency of e-flows can match the shape of the natural hydrograph. During the dry months the e-flows in this case take up nearly 100% of the river flow, while in the wet season, only approximately half, this meaning that the allocatable water is mainly available during the wet season (i.e., for the Niger River). Just how much of the water is available for abstraction and allocation, and at what times of the year, is the subject of an e-flows determination, designed to ensure that the river ecosystem continues to provide services to society and at the same time protect the ecosystem resource base.

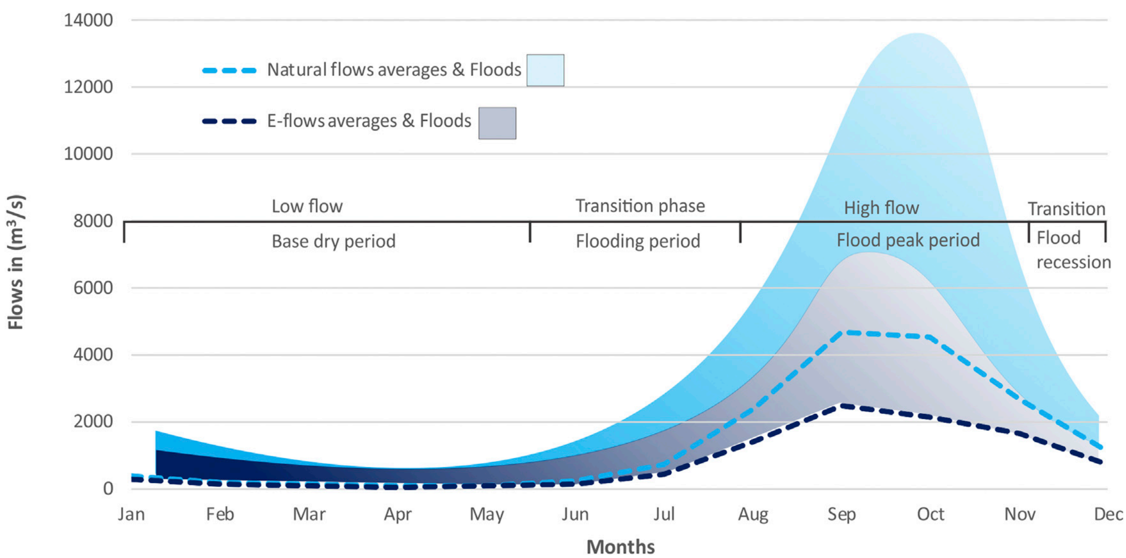

FIGURE 5 | Graphical representation of the monthly average and flood hydrograph, and the environmental flows of the Niger River in Mali. The dotted lines represent the monthly averages, and the shaded areas the flood peaks (reference Dickens et al., 2018).

Hydropower and e-Flows in Uganda

In Uganda, the National Water Policy (GoU, 1999) and the National Water Act (GoU, 1997) that direct the sustainable development of water resources, do not explicitly mention e-flows. However, the national water policy does state that water should be allocated to the environment and particularly water resources should be managed to provide a minimum flow to maintain water quality and aquatic ecosystems, but without providing guidance on how to achieve this or how much may be required (GoU, 1999:30). In an examination of the applicability of e-flows within Uganda (Okori, 2010), it was found that the basis upon which minimum flows of water permits have been developed did not incorporated minimum flow requirements for ecosystem health. One of the first government documents to recognize e-flows was the Environment Impact Assessment Guidelines for Water Resources Related Projects in Uganda (GoU, 2011:77). It advocated environmental awareness training and the evaluation of river flow requirements in relation to planned water projects. Following on from this, the Water Supply Design Manual stressed the residual ecological and Environmental flows of rivers has to be guaranteed in the context of water supply abstraction (GoU, 2013:54). This manual suggests that to determine the e-flows of a river, the model should consider hydraulics, hydrology, meteorological and biological parameters. Environmental flow requirements have also been included in Environmental and Social Impact Assessment (ESIA) for hydropower projects, recommending that weir design should be subjected to unconditional minimum flow requirements at approved flow rates to be determined by the Department of Water Resources Management (GoU, 2018:96). Furthermore, the recent Uganda Catchment Management Planning Guidelines (GoU, 2019) acknowledge the need for e-flows for environmental sustainability, stating that 'the amount of existing water use must be taken into account, as well as the amount of stream flow that is needed to maintain critical seasonal flows for water quality management, environmental and ecological requirements, and to protect water off-takes that depend on river water levels to function (GoU, 2019). However, it also highlights the lack of data and policies needed to establish e-flows requirements in Uganda (GoU, 2019).

In the absence of explicit e-flows guidelines for Uganda, the Nile Basin Initiative strategy on e-flows, of which Uganda is a member, provides suitable direction for e-flows implementation that conforms to best e-flows practice (Nile Basin Initiative, 2016; Nile Basin Initiative, 2017; O'Brien et al., 2018). This strategy provides context of e-flows management at local, regional and basin scales and describes how this can be achieved in consideration of other users of the Nile Basin. The strategy then describes the e-flows framework and guiding principles for managing e-flows in the Nile Basin.

Opportunities for e-flows management in Uganda were workshopped with the Electricity Regulatory Authority of Uganda, national regulators, specialists and stakeholders in Kasese in 2018. This workshop included a series of site visits and formal and informal discussions between stakeholders pertaining to water resources development, hydropower in Uganda and e-flows. Stakeholders represented at the workshop included; government regulators, conservationists, developers, development beneficiaries and impacted and affected parties. During this workshop stakeholders discussed challenges to the implementation of good e-flows policy, including implementation of the Nile e-flows strategy in Uganda, particularly amongst government regulators (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2018). The primary concerns included: there is an incomplete understanding of the meaning of e-flows and how to integrate these into strategies and day to day management; a lack of regulations or strategies allied to the policy for the management of e-flows; inappropriate methodologies and/or level of detail in setting e-flows requirements, as well as inefficient procedures, resulting in loss of staff time and supporting resources, loss of power generation and grid stability in critical supply situations, and environmental degradation and social safeguard issues; inadequate capacity for compliance monitoring of e-flows requirements also resulting in loss of staff time and supporting resources, and/or environmental degradation and social safeguard issues. These shortcomings formed the basis of this paper. Resolution is urgently needed to ensure proper management of the water resource. An additional concern is that hydropower developers and operators are also involved in the management of hydropower activities themselves, in that they have to comply with government regulations, including those for e-flows. The same officials are often involved in development and authorisations resulting in a conflict of interest. There appears to be a general lack of guidance from government agencies during project conception and design, resulting in inefficient planning, exacerbated by largely non-transparent government procedures resulting in inconsistent setting of e-flows requirements by concerned government agencies and thus an uneven field of competition between (private) developers. The lack of proper regulations has also resulted in the somewhat arbitrary setting of e-flows requirements by concerned government agencies, leading to projects sometimes becoming economically non-viable. Furthermore, developers have also complained that disproportionate e-flows requirements need to be sustained during operations, thus limiting generation and the resulting viability of the development. There was also a perceived lack of knowledge about the management of dams and power plants to provide for e-flows, thus this paper.

Riparian (and other) stakeholders are vulnerable to threats associated with unsuitable management of e-flows that results in loss of ecosystem services to stakeholders in downstream river basins in particular (Mander et al., 2017; O'Brien et al., 2018). This may be due to deterioration of aquatic and related ecosystems in their immediate vicinity, resulting in lost opportunities and natural capital (Mander et al., 2017).

Given the above situation, there is need for an improvement of the regulation of e-flows by government agencies, together with a need for developers to factor in more confident estimates of e-flows together with an understanding of how hydropower affects the ecosystem and the people who rely on this ecosystem. Consideration thus needs to be given to the existing legal framework and how this may be developed into

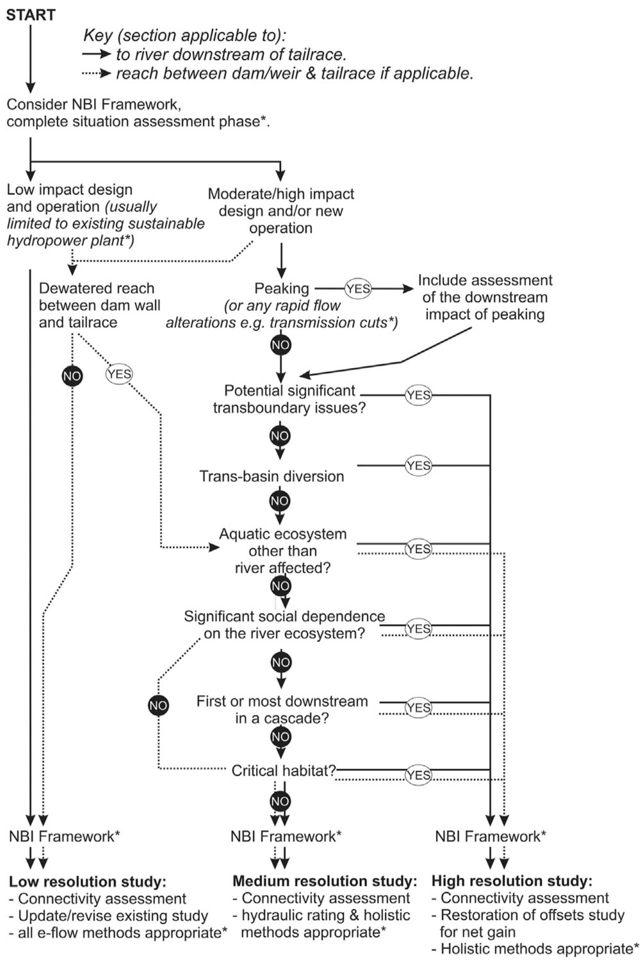

FIGURE 6 | Decision support system (tree) for environmental flow assessments for small scale (<50 MW capacity) Hydropower development in Uganda. Solid line and dotted line represents pathway for e-flow consideration downstream of tailrace and hydropower plant and the dewatered zone or reach between diversion weir and tailrace respectively. If both attributes of a hydropower plant development are appropriate then both lines should be considered in a precautionary manner where preference for high resolution, holistic methods are afforded. Adapted from World Bank (2018) and Nile Basin Initiative (2016).

future policy, strategies and regulations; system scale water resources planning with basin level e-flows determination, supporting the mid-to longer-term pipeline of larger scale hydropower projects including those on the Nile, but also clusters of small schemes in mountainous areas; improving e-flows releases of existing operations, e.g., the ecological optimization of releases and compliance monitoring; and lastly, specific issues, such as sites in national parks, mitigation of impacts of hydropower peaking, design and operation of fish ladders all need consideration.

Regional Integration

Being located within the larger Nile River Basin, the most relevant NBI document for the management of e-flows in Uganda is the "Strategy for the Management of E-flows in the Nile Basin" (Nile Basin Initiative, 2016). The strategy was prepared by the Nile Technical Advisory Committee (NILE-TAC) and Nile Basin Environmental flows Expert Group through the course of the "Preparation of NBI Guidance Document on Environmental flow" (Nile Basin Initiative, 2016). The goal of the strategy is to: "facilitate and develop a culture of incorporation of collaborative, best practice e-flows management into the water resource planning, management and policies of the countries who share the Nile Basin (short term) to ultimately result in the establishment of an integrated, basin scale e-flows management system (long term)". Finally, the strategy advocates the allocation of water resources in a manner that does not jeopardize the functioning of the resource. The strategy also supports international conventions and agreements that consider the sustainable management of water resources and specifically Environmental flows. These include: 1) consideration of the Sustainable Development Goals (SDGs), 2) requirements of the Convention on Biological Diversity, of which Uganda is a member, 3) the Aichi Biodiversity Targets for 2020 and 4) the RAMSAR guidelines for the allocation and management, including e-flows, of water resources in a sustainable manner (Nile Basin Initiative, 2017). These regional policies align to advocate "good" e-flows practices that are summarized in the NBI e-flows strategy and include involvement of stakeholders in a governance system aimed at subsidiarity, keeping e-flows assessments as simple as is necessary, applying adaptive management principles and so to continuously learn from application, sharing experiences and possibly expertize across the basin, and lastly to be willing to manage e-flows at multiple scales (from local to basin).

Recommendations for E-Flows Methods and Approaches

Good practice e-flows management in Uganda has the potential to make a noticeable contribution to the sustainable development of the water resources of Uganda, this includes small-scale hydroelectric power generation. The point of departure for good e-flows management practice is to ensure that management efforts meet the definition of e-flows, defined above (Arthington et al., 2018). Then it is important to identify roles and responsibilities of stakeholders and types of activities that may affect water resources that triggers the need for e-flows management activities (World Bank, 2018). The NBI e-flow strategy (Nile Basin Initiative, 2017) and Nile Basin e-flow framework (Nile Basin Initiative, 2016) and guiding elements for best practice in e-flows (Poff et al., 2018) all provide good-practice direction on the roles and responsibilities of different stakeholders who are responsible for e-flows assessments. Formal national custodians of water resources should be responsible for large-regional and or basin scale e-flows management, which includes sustainable development of water resources and meeting the needs of local communities and the people who depend on these resources for survival. In Uganda, government representatives of the Ministry of Water and Environment and Electricity Regulatory Authority in particular are primarily concerned with hydropower development and water resource management to manage regional and basin scale e-flows in Uganda, and contribute to Nile Basin management. These regulatory stakeholders issue authorization for local and reach scale developments in consideration of the contribution of activities to larger regional management endeavors. Developers are required to obtain authorization for developments that must address local, reach and on occasion regional scale effects of activities/developments. Ultimately the decisions on how to manage the balance between the need to use and protect water resources is socio-political (Dickens et al., 2018), with society deciding what constitutes an acceptable risk to the ecosystem, above the sustainability threshold, in terms of the benefits that are gained from the ecosystem. The more the ecosystem is "used", the greater the risk becomes that it may fail to provide further resources, in which case both the ecosystem and society will have suffered loss (Dickens et al., 2018). By putting e-flows in place, and only using the "allocatable" amounts that do not impinge on the e-flows, society will be ensuring its own future as the ecosystem will continue to produce benefits for society.

The World Bank (2018) has developed a Good Practice Handbook for E-flow (WB-GPH) for Hydropower Projects, especially for the guidance of hydropower activities in the private sector in emerging markets or developing nations. This WB-GPH provides information on the potential effects of hydropower on water resources, e-flows assessments, methods and tools and provides a decision support tree for selecting e-flows methods for individual projects, e-flows and adaptive management and terms of references for e-flows assessments (World Bank, 2018) (**Figure 6**). Consider also that once operational the Nile e-flow framework may provide low confident e-flows requirements for all major rivers and tributaries in the Nile Basin (Nile Basin Initiative, 2016). With this information, and an understanding of the development and operational requirements for new hydropower plants more robust, more confident e-flows can be determined. The World Bank (2018) decision tree for e-flows assessment recommends low, medium or high-resolution e-flows determination for all hydropower activities depending on the potential attributes of proposed developments including: constriction of barriers; existence of a dewatering reach; plan for peaking; vulnerable ecosystems and ecosystem attributes including critical habitats; social dependence on existing resource and transboundary and regional effects. When undertaking e-flows assessments the following good-practice guiding elements obtained from Poff et al. (2018) and principles for e-flows management obtained from Nile Basin Initiative (2017) should be considered:

1) Engage stakeholders in the entire e-flows determination process, particularly in the visions and objectives determination process.
2) Ensure benefits of water resource allocation and or developments are shared between local and regional stakeholders.
3) Environmental flows attempt to achieve a sustainable balance between the protection of water resource and the needs of society to use them. This is a trade-off that needs to be made by society, in the context of regional use and protection scenarios/opportunities, and needs to be informed by evidence that describes the ecosystem. Consider also the downstream vs. upstream effects of flow and non-flow stressors.
4) In e-flows assessments carefully identify what can be attained (and what cannot) from an implementation of e-flows regimes. Apply requisite simplicity concepts to processes and only make the assessments as complicated as necessary.
5) Consider how environmental water goals and applications embed within and interact with other realms of influence that emerge with water governance and management at system scales.
6) Clearly identify at what spatial and temporal scale e-flows applications are appropriate and intended.
7) Environmental flows assessments should be evidence based and flow-ecology and flow-social relationships should be described in a clear and quantitative manner.
8) Use appropriate e-flows determination methods that are transparent and robust. Ensure that uncertainty associated with the methods are explicitly presented.
9) Incorporate nonstationary and process-based understanding into e-flows science and implementation to meet a new future.
10) Make efforts to engage with the proponents and engineers of new water infrastructure developments or proposed relicensing opportunities for existing infrastructure.
11) Embrace adaptability principles of learning while doing and attempt to introduce adaptive management into e-flows practices where new information is integrated into the management processes and outcomes are flexible and can be adjusted as they are implemented and monitored.

From the emergence of e-flows determination procedures in the early 1990s many methods have been established and reviewed (Tharme, 2003; Petts, 2009; Poff et al., 2018; Brown et al., 2020 for example). Available methods can be grouped into four main categories including: 1) hydrological, 2) hydraulic rating, 3) habitat simulation (or rating), and 4) holistic, with some recent developments of holistic methods into frameworks for e-flows assessments of large regional scales (Poff et al., 2018). Methods differ in complexity, uncertainty, cost and time resources to determine e-flows. Consider the Appendix for detailed comparisons between methods and some advantages and disadvantages associated with the use of available e-flows methods. For planning purposes, the hydrological, hydraulic rating and habitat simulation methods are commonly applied. For developments habitat simulation and holistic methods dominate (Tharme, 2003; Poff et al., 2018). Consideration of regional implications and the Nile e-flow framework should then be considered (Nile Basin Initiative, 2016). The methods tend to be applied hierarchically (Tharme, 1996; Poff et al., 2018), often starting from hydrology-based approaches which are more appropriate in a precautionary, low-resolution framing of environmental water requirements at a water resources planning level, to increasingly comprehensive assessments using holistic methods where the importance of certainty in the results is much greater. Although e-flows determination methods are dominated by riverine ecosystem methods, some methods allow for the consideration of estuaries, wetlands, lakes ecosystems and ground water ecosystems for example (King and Louw, 1998; Hughes and Louw, 2010; King, Brown and 2010; O'Brien et al., 2018).

When e-flows assessments are undertaken in Uganda good practice requires consideration of the requirements of the Nile e-flow framework for regional scale application of e-flows (Nile

Basin Initiative, 2016). This will allow evidence collected from site and reach scale e-flows assessments to contribute to regional scale assessments and inferences to other sites with similar socio-ecological characteristics (Nile Basin Initiative, 2016). The Nile e-flow framework consists of seven phases summarized briefly in the context of e-flows for small hydropower developments:

1) Situation Assessment and Alignment Process phase: in this phase review all information pertaining to water resource management and e-flows associated with the proposed development. Use of the Nile e-flow framework checklist is recommended (Nile Basin Initiative, 2016).
2) Resource Quality Objectives Setting phase: targets and or a vision for a sustainable balance between the use and protection of water resources is required. These examples should be considered in site scale e-flows assessment as well as documented to contribute to a understanding of objectives for larger scales (Nile Basin Initiative, 2016).
3) Hydrological Foundation phase: in this phase of the framework hydrological statistics and associated understanding of the volume, duration, frequency and timing of flows is determined. This approach is well defined in the framework and should be considered to direct site scale assessments that can contribute to regional scale assessments (Nile Basin Initiative, 2016).
4) Ecosystem Type Classification phase: the framework and its ability to extrapolate flow-ecosystem and flow-ecosystem service relationships and information pertaining to the effects of flow and non-flow stressors on ecosystems is dependent on knowledge of the ecosystem characteristics. Collecting this data for site scale e-flows assessments is paramount for the application of the framework and good-practice for site scale assessments (Nile Basin Initiative, 2016).
5) Flow Alterations phase: knowledge of how flows will change due to hydropower developments is a fundamental requirement of good-practice e-flows assessments. This information and how accurate e-flows assessments were established to mitigate the effects of altered flows is important information for the Nile e-flow framework (Nile Basin Initiative, 2016).
6) Flow-Ecological-Ecosystem Services Linkages phase: all good-practice e-flows assessments must be based on understanding of flow-ecosystem and flow-ecosystem service relationships. Usually site scale e-flows assessment have opportunities to collect quantitative evidence that supports local e-flows assessments and will contribute to the application of the framework (Nile Basin Initiative, 2016).
7) Environmental flows Setting and Monitoring phase: in this phase of the framework, appropriate holistic e-flows assessments are implemented that benefit from data available in the catchment. This phase also includes an adaptive management component all of which can benefit from site scale applications.

Figure 6 provides a synthesis of the World Bank (2018) decision tree for e-flows assessments for hydropower and where the Nile e-flows framework (Nile Basin Initiative, 2016) in the context of small hydropower developments in Uganda.

CONCLUSION

Stakeholders of the small-scale hydropower sector in Uganda recognize the need to balance resource development that contributes to the livelihoods of vulnerable African communities, and sustainable ecosystems from which vulnerable human communities derive services. Environmental flows principles and practices are available to contribute to sustainable hydropower development and protect socio-ecological systems for present and future generations. Uganda is currently simultaneously in the process of developing hydropower plants and e-flows policies with limited guidance on e-flows management. Environmental flows management concepts have developed from the 1990s into an international good practice that contributes to sustainable water resource developments. We have provided a synthesis of existing good e-flows practices for consideration by the small hydropower development sector in Uganda, including methods and their appropriate use and consideration at multiple spatial scales and for regional policies and frameworks.

The determination and management of e-flows in the hydropower sector in Uganda is largely dependent on the availability of and quality of hydrology, hydraulic and flow-ecosystem and flow-ecosystem service relationship information. Unfortunately major constraints to regional e-flows program developments that may have considerable negative socio-ecological and economic benefits includes data ownership and secrecy, poor data capturing resulting in loss of information, and the lack of transparency of evidence collected. This review of good-practice e-flows practices that is applicable to the small hydropower sector in Uganda, and considers regional developments, can support the sustainable development of water resources in Uganda for a better future for all of its vulnerable communities and the environments they depend on.

AUTHOR CONTRIBUTIONS

GO'B conceived the idea of the research in collaboration with the team, collected and evaluated information and wrote the manuscript. CD also contributed to the idea of the research in collaboration with the team, formatted the content of the manuscript, collected and evaluated information and co-wrote, edited the manuscript. CM also contributed to the idea of the research in collaboration with the team, formatted the content of the manuscript, collected and evaluated information and co-wrote, edited the manuscript. ME also contributed to the idea of the research in collaboration with the team, and co-wrote, edited the manuscript.

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