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Beyond the Banks: Paving the way for environmental flows in Nepal

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ABSTRACT

Nepal has huge hydropower potential. Although the concept of environmental flows (e-flows) emerged in the early 2000s, its integration into hydropower development remains in the early stages. This study represents the first comprehensive effort to evaluate key stakeholders' awareness of e-flows and identify the major challenges hindering their mainstream adoption in Nepal's hydropower sector. Furthermore, it documents stakeholders' perceptions regarding the impact of hydropower development on aquatic biodiversity and river ecology. An extensive survey was conducted between December 2022 and January 2023, collecting responses from a diverse group of stakeholders, including government agencies, water resource developers, user groups, practitioners, researchers, and academics. Additionally, focus group discussions were held in the Karnali River basin of western Nepal. The findings reveal that only 50 % of respondents are familiar with the e-flows concept. However, 80 % believe that e-flows have not been adequately implemented in any existing hydropower projects in the country. Similarly, 72 % of respondents perceive that hydropower development leads to biodiversity loss, while 56 % believe it reduces downstream water flow. The key challenges identified include (a) inadequate follow-up on environmental impact assessments (EIAs), (b) weak regulatory enforcement, (c) insufficient civil society oversight for ensuring compliance with EIA recommendations, (d) limited technical expertise, and (e) the absence of user-friendly e-flow estimation methods. The study's findings provide valuable insights for policymakers to promote sustainable water resources development and mitigate the ecological impacts of hydropower projects.

1. Introduction

Increasing worldwide demand for freshwater supplies to fulfill domestic, industrial, agricultural, and energy requirements has led to the construction of storage dams, diversions and control structures, thereby altering the rivers' natural flow. The changes in the quantity and quality of natural river flows adversely affect the physical, chemical, and biological characteristics of water bodies, contributing to widespread environmental degradation (Mirchi et al., 2014; UNESCO, Unwater). River damming, often for hydropower generation, reduces seasonal and inter-annual streamflow variability of rivers (Poff et al., 2007). Reduced flow obstructs river connectivity and creates several river fragments with little or no water (Grill et al., 2019; Lehner et al., 2011). Consequently, this impedes fish movements to feeding or spawning grounds and limits dispersal (Barbarossa et al., 2020).

Besides limiting fish movement, dams lead to the homogenization of flow regimes, bringing changes in nutrient and sediment transport and increasing water temperature, which contributes to the proliferation of non-native species (Pompeu et al., 2022; Carvalho et al., 2025). Many fragmented reaches are affected by an increase in non-native species, often at the expense of native ones, leading to declining biodiversity (Carvalho et al., 2025; Vörösmarty et al., 2010; Feio et al., 2025). In order to minimize the adverse effects of dams on downstream ecosystems, outflows modifications have been implemented in recent years (Gillespie et al., 2015). These efforts aim to restore river flow patterns to pre-dam conditions (Bednarek and Hart, 2005), sustaining flow–ecology relationships and ensuring good water quality necessary for both aquatic communities and societal needs. This concept led to the development of environmental flows (e-flows) (Arthington et al., 2018). Arthington et al. (Arthington et al., 2018) defined e-flows as "the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies,

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sustainable livelihoods, and well-being", a definition based on the modified Brisbane declaration (Brisbane Declaration 2007). E-flows are also referred to by various other terms, including in-stream flows, ecological flows, normative flows, ecological base flows, water for nature, minimum flows, environmental demand and environmental water requirements (Arthington et al., 2010; Davis et al., 2015; Eriyagama and Jinapala, 2014; King et al., 2015).While some of these terminologies represent a holistic approach of flows required to meet all dimensions of riverine ecosystems, "in-stream flows" specifically overlook the lateral connectivity between riverine and terrestrial ecosystems (King et al., 2015; Dyson et al., 2003). .

Integrating environmental flows (e-flows) assessments into water management and policy is crucial for ensuring water sustainability for both humans and ecosystems (Tharme, 2003; Smakhtin, 2004; Pahl--Wostl et al., 2013). Over the past 40 years, more than 207 e-flow methods have been developed globally, categorized into hydrological, hydraulic rating, habitat simulation, and holistic approaches (Tharme, 2003; Arthington et al., 2004).

Hydrological methods were the first to be developed and continue to evolve (Tharme, 2003). They are widely used in e-flows estimation, making up about 30 % of all described methods (Tharme, 2003). These methods use long-term time series river flow data, typically 30 to 50 years, collected from multiple locations along a river. Examples include the Range of Variability Approach (RVA), Tennant's method, Flow Duration Curve (FDC), and Indicators of Hydrologic Alteration (IHA) (Tharme, 2003). The second category, hydraulic rating methods, assumes a relationship between flow volume and changes in hydraulic variables (e.g., depth, wetted perimeter, and width) across a single river –section as a surrogate for habitat factors limiting to target biota (Tharme, 2003; Gopal, 2013). Examples of hydraulic rating methods involve wetted perimeter methods, the toe-width method, riffle analysis, the adapted ecological hydraulic approach, and flow event method and lotic invertebrate index for flow evaluation (LIFE). The third category, habitat simulation methods, uses elements of hydraulic methods to determine the optimal water needs for target species (Gopal, 2013). Habitat simulation methods are also known as Habitat Modelling Methods, Habitat Rating Methods or Microhabitat Methods. Examples include Habitat Quality Index (HQI), In-Stream Flow Incremental Methodology (IFIM), Physical Habitat Simulation Model (PHABSIM), etc. The fourth category, holistic methods, considers the whole riverine ecosystem and seek to modify flow regimes to resemble the natural flow regimes, ensuring the ecological integrity of the river (Arthington et al., 2004; Gopal, 2013). Examples include Building Block Methodology (BBM), Downstream Response to Imposed Flow Transformation (DRIFT), Ecological Limits of Hydrologic Alteration (ELOHA) etc. These methods have been designed and/or applied in various river basins, particularly in developed countries (Tharme, 2003; Smakhtin, 2004; Arthington et al., 2004) and more recently in Asian countries (Kumar and Jayakumar, 2020; Chen and Wu, 2019). However, implementation faces several challenges across the regions (Table 1).

Proper calculation of e-flows is essential for maintaining good ecological conditions in the reaches downstream of a dam. This is particularly important for a country like Nepal, where significant strides in hydropower generation are underway (Department of Electricity Development 2025; Nepal Commission Planning/Government of Nepal 2020). The country aims to generate 28,500MW by 2035 through private companies and state-owned projects as indicated in Energy Development Roadmap-2081 (Department of Electricity Development 2025; Nepal Commission Planning/Government of Nepal 2020; Electricity Regulatory Commission Nepal ERCN, 2024). As of May 2025, Nepal generates 3330 MW from 170 hydropower projects of more than 1 MW, and 9 MW through 13 projects lesser than 1 MW. Similarly, an additional 256 hydropower projects with >1 MW installed capacity have acquired construction licenses, with a total capacity of 10256MW (Fig. 1). Western Nepal, particularly the Karnali and Mahakali River Systems, possesses immense hydropower potential, estimated at 26,570 MW (Rauniar, 2022). The Karnali River is the longest river with a 507 km length in Nepal and is formed by merging seven major tributaries. A 202 km long "West Seti River" and a 264 km long Bheri River are the two major feeders that join the Karnali River in different sections. The average discharge of the river is about 1369 m3/s (Khatiwada et al., 2016). Due to the highly torrential nature of the Karnali River, it is estimated to produce 14,150.80 MW hydropower generation (Prajapati, 2015). Despite this potential, the region currently contributes just 5.92 % (197.67 MW) to the country's total power generation (Department of Electricity Development 2025), even though it was reported to hold 46 % of the projects included in the 16,974 MW feasibility licenses issued nationwide (Rauniar, 2022). Mega projects such as Mugu Karnali (1902 MW), Upper Karnali Hydroelectric Project (900 MW), Betan Karnali Hydroelectric Project (439 MW), and Phukot Karnali Hydroelectric Project (480 MW) are likely to be constructed in the near future due to the possibility of cross-border trade with India (Department of Electricity Development 2025).

Table 1
List of major challenges identified for e-flows implementation in different countries across the world.

S. N.	Challenges identified for e-flows implementation	References
1	Political will	(Moore, 2004; Le Quesne et al., 2010)
2	Lack of understanding of socio-economic costs and benefits	(Moore, 2004; Le Quesne et al., 2010; Hirji and Davis, 2009)
3	Legal, institutional, and monitoring arrangements	(Moore, 2004)
4	Financial resources	(Moore, 2004; Le Quesne et al., 2010; Hirji and Davis, 2009; Wineland et al., 2022)
5	Expertise and technical knowledge in modeling and scenarios development linking biophysical and socioeconomic impacts	(Chen and Wu, 2019; Moore, 2004; Le Quesne et al., 2010; Hirji and Davis, 2009; Wineland et al., 2022)
6	Effective stakeholder involvement	(Moore, 2004)
7	Public acceptance	(Moore, 2004; Hirji and Davis, 2009)
8	Hydrological data on both temporal and spatial scale	(Chen and Wu, 2019; Moore, 2004; Hirji and Davis, 2009; Poff, 2018)
9	Incorporating the whole water cycle (surface, and groundwater) into the assessments	(Hirji and Davis, 2009)
10	Applying environmental flow assessments to land use activities that intercept and exacerbate overland flows	(Hirji and Davis, 2009)
11	Integration of climate change in the assessments	(Hirji and Davis, 2009; Wineland et al., 2022)
12	Lack of authority to implement e-flows in water governance structures	(Wineland et al., 2022)
13	Fragmented water governance in trans-boundary water systems	(Wineland et al., 2022)
14	Non-stationarity (climate change-induced alteration in river flow regimes including frequent extreme events such as floods and drought)	(Poff, 2018)
15	Shifting from static to dynamic modeling	(Chen and Wu, 2019; Poff, 2018)
16	Broadening the ecological foundation towards a more predictive e-flows science	(Poff, 2018)

The Mahakali is a trans-boundary basin with a total catchment area of 15,260 sq. km at Banbasa barrage, of which 35.4 % lies in the Nepalese side (Mool et al., 2001). The river, originates from Api Himal, is about 223 km long and confluences with the Ganges in India. On the Nepalese side, Chamelia and Surnagad are two major tributaries of the Mahakali River.

Chamelia is a snow-fed river with a catchment area of 1603 km^2. The river alone contributes about 28 % of 7789 million cubic meters, which is the total average annual runoff contributed by all tributaries on

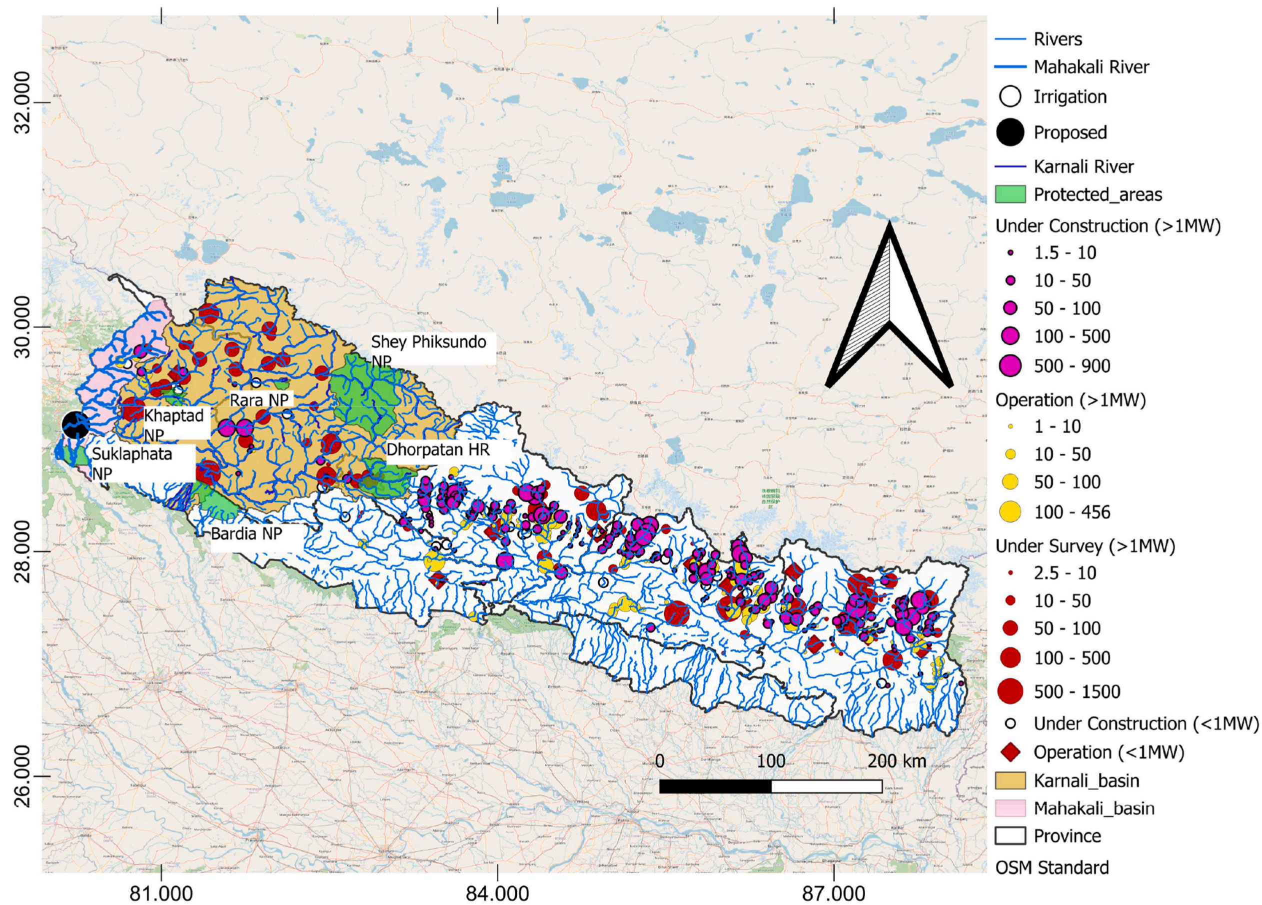

Fig. 1. Locations of major hydroelectric projects including operation, under construction, proposed and survey license, as of May 2025, DOED (Department of Electricity Development). The size of a circle indicates hydropower generation capacity. NP represents National Park and HR represents Hunting Reserve.

Nepalese side. In recent years, Chamelia River has been a center for hydropower development, with five projects at various stages. The projects have capacities ranging from 4 MW to 85 MW, contributing to a total planned capacity of 200 MW, of which 75 MW and 85 MW are operational and under construction, respectively (Department of Electricity Development 2025). Moreover, a mega bi-national Pancheshwor Multipurpose Project (PMP), with a planned capacity of 6720 MW, is proposed for construction on the Mahahaki River System (Pancheshwar Multipurpose Project).

Similarly, many small-scale irrigation projects and micro-hydropower have been constructed on many tributaries of both river systems (Tachamo-Shah et al., 2020). These projects have already altered or fragmented the majority of small- to medium-sized tributaries in the region (Tachamo-Shah et al., 2020). As a result, downstream river reaches are mostly colonized by warm-water-adapted species or non-rheophiles (Tachamo-Shah et al., 2020). The upcoming numbers of large water infrastructures in the region is likely to create several kilometers of dewatered zones downstream of their respective dams if not properly regulated. Therefore, timely e-flows assessments are crucial to mitigating the adverse impacts of hydropower development on the functioning of river ecosystems, biodiversity and associated societal benefits. As in many parts of the world, the ecohydrological status and ecosystem services of Nepalese river ecosystems will depend on the calculated e-flow values and on decisions to implement them in practice.

In Nepal, several legal mechanisms have been implemented to protect riverine ecosystems during water resource development. The Water Resources Act, 1992 was the first stepping stone towards the e-flows, mandating environmental studies for water resource development projects. The Environmental Protection Act, 2019 emphasized the need for an Initial Environmental Examination (IEE) and an Environmental Impact Assessment (EIA) based on the installed capacity in the projects (Government of Nepal (GoN) 2019). The promulgation of the Environmental Protection Rules, 2020 made it mandatory to conduct an IEE for hydropower projects below 50 MW and an EIA for above 50 MW (Government of Nepal (GoN) 2020).

The "Hydropower Development Policy, 2001″ introduced the concept of e-flows in the country, and defining it as the release of discharge of 10 % of the mean of the dry period or quantum defined by the EIA report during the operation of the hydropower projects (Ministry of Water Resources (Now Ministry of Energy)/GoN 2001). A recent provision on e-flows has been made by the Ministry of Forests and Environment, Government of Nepal through the Land Acquisition for the Construction of Physical Infrastructure Inside Protected Areas (Procedures), 2023 (Ministry of Forests and Environment, Government of Nepal (MoFE, GoN) 2023). This provision explicitly defines e-flows requirements for the construction of physical infrastructures including dams, diversion channels, headworks, penstocks, and powerhouses, either entirely or partly inside protected areas (PA), depending upon the hydropower capacities, i.e., 25 MW, 25 - 100 MW and 〉 100 MW (Ministry of Forests and Environment, Government of Nepal (MoFE, GoN) 2023). A Protected Area is a geographic entity designated for the conservation of biological diversity and natural scenery in situ. The government of Nepal identifies six types of Protected Areas such as National Parks, Wildlife Reserves, Hunting Reserve, Conservation Areas, Ramsar Sites and buffer zones.

Despite continuous governmental interventions over the past two decades, the application of the e-flow assessments primarily based on Hydrological Methods has been mainly limited to research, testing, and validation in different river systems across Nepal (Table 2).

Furthermore, even with the recent development of the river basin-specific Holistic Method - WENEFC [(International Water Management Institute 2019), Table 2] - the actual implementation of e-flow assessments has not significantly improved. To address this issue, a comprehensive study was carried out to i) assess people's perceptions of the benefits and adverse impacts of hydropower development on river ecosystems, ii) evaluate their awareness of the e-flows concept, e-flows estimation methods, and the significance of mainstreaming e-flows into hydropower developments and iii) document the major barriers and constraints associated with mainstreaming e-flows in the country. The study employed a comprehensive survey across a range of stakeholders including, government agencies, non-governmental organizations (NGOs), water-user groups, hydropower developers, EIA practitioners, and academicians. Furthermore, focus group discussions (FGDs) were conducted in the Karnali River basin. This study represents an initial effort to gather people's perceptions and interpretations of environmental flows and to capture their perspectives within the Nepalese context. Based on the study findings, we ranked major barriers and identified recommendations for mainstreaming e-flows in Nepal.

2. Methods

Primary data were collected through structured questionnaire surveys administered via online Google Forms, interviews with key personnel in Karnali province and focus group discussions (FGDs) with riparian communities of the Karnali River. To develop the questionnaire, an extensive review of online databases such as Google Scholar, ResearchGate, and PubMed were searched extensively to identify studies and practices related to environmental flows (e-flows) both nationally and globally. A systematic review was carried out, focusing on three key terms (a) Environmental flow or e-flow, (b) water resource development, and (c) Environmental flow and perception. These terms were searched in web-based search engines to find journal articles and reports published in the last 3 decades (1990–2023). The literature was scanned for titles and abstracts and reviewed the full text of pertinent studies. This information included details about the e-flows method, data requirements, time frame, and objectives. Based on the literature review, a set of relevant questions/ indicators were developed, covering the following: i) the benefits and consequences of hydropower development in the country, ii) familiarity with e-flows methods, iii) e-flows practices in hydropower development, and iv) challenges in implementing e-flows in hydropower projects. The drafted questions were then shared with water resource experts, policymakers, and hydropower IEE/EIA practitioners for their suggestions and feedback. After incorporating their input, the questionnaire was finalized.

The final questionnaire consisted of 29 questions (Supplementary 1). The first section of the questionnaire was designed to collect respondents' personal details including their name, gender, contact number, area of expertise and workplaces. The second section, covering questions 1 to 29, examined respondents' awareness of the positive benefits of hydropower development, the environmental and social impacts of hydropower projects on aquatic ecosystems and local communities, familiarity with e-flows methods, the significance of e-flows assessment, and the challenges associated with its implementation in hydropower project development.

The complete questionnaire was designed as an online Google Form survey and shared with key stakeholders representing academia, governmental agencies, practitioners, developers and non-governmental organizations.

For the selection of key stakeholders, firstly, an inventory of relevant organizations was created covering governmental and non-governmental organizations (NGOs). This list covered regulatory bodies, academic institutions, hydropower companies, funding agencies, and community-based organizations. A total of 110 contacts were identified, consisting of individuals working or affiliated with

Table 2
List of e-flows exercises in different river systems of Nepal along with major findings of the assessments.

S. N.	Methods, Areas and Time	E-flows findings	References
1	This is the first known environmental flows assessment in Nepal; carried out in a 20 km river stretch of the East Rapti River in 1999.	The primary focus of the study was to establish the minimum river discharge and water depth in East Rapti, located at the border of the Chitwan National Park to facilitate tourist activities such as ferry and boat operations. It was assumed that setting a minimum flow would simultaneously support the park's riverine ecosystems and the livelihoods of local communities. The proposed discharge of 15 m^3s^1 was expected to maintain a water depth of 1 m, a velocity of 0.3 m s^{-1} and a river width of 50 m in the river, which was considered sufficient for boat operations. However, this value was not calculated from any established environmental flow methods, nor was the mean annual runoff (MAR) estimated in the study. Therefore, the study highlighted the need for further study in the area (Smakhtin et al., 2006).	[(International Water Management Institute (IWMI) 2000) cited in (Smakhtin et al., 2006)]
2	Different hydrology-based environmental flow assessment (EFA) methods such as Tennant (Tennant, 1976), desktop reserve model (Hughes and Hannart, 2003), range of variability approach [RVA, (Richter et al., 1997)] were tested in the East Rapti River in 2005.	The study showed the adaptability of existing hydrological methods to simplify e-flows assessment procedures, even in situations where local eco-hydrological knowledge is lacking while ensuring compliance with flow variability principles. Nevertheless, some challenges persist, with some existing techniques like Tennant's being overly simplistic and others being overly complex, potentially not incorporating recent eco-hydrological advancements. Additionally, specific tools, such as DRM (Desktop Reserve Model) or RVA (Range of Variability Approach), designed for the particular regions, required further development, testing, and recalibration when applied in new territories, often resulting in substantial	(Smakhtin et al., 2006)

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Table 2 (*continued*)

S. N.	Methods, Areas and Time	E-flows findings	References
		costs and potential technical capacity constraints.	
3	Six hydrological based e-flows models such as the Global Environmental Flow Calculator (Smakhtin and Eriyagama, 2008), the Tennant method, the flow duration curve method, the dynamic method, the mean annual flow method, and the annual distribution method were implemented in the Kali-Gandaki River System.	The study revealed that the annual distribution method and the 30 % Q-D (30 % of daily discharge) are the most suitable methods for e-flows implementation in the Kali Gandaki River System as these two methods showed lower alterations in various global indexes for each group of Indicators of Hydrological Alterations and e-flows components.	(Suwal et al., 2020)
4	A desktop-based e-flow assessment software called the "Western Nepal Environmental Flow Calculator (WENEFC)" is a modified version of the "Global Environmental Flow Calculator". It was developed to determine environmental flows in the rivers of the Karnali-Mohana and Mahakali River Systems in western Nepal. The e-flows estimation involves two approaches: the Hydrological method, and the Holistic method. The "Hydrological method" follows the procedure developed by Smakhtin and Anputhas (Smakhtin and Anputhas, 2006). The "Hydrological method" was built by incorporating simulated monthly flow values at 157 locations on the two river systems, while the "Holistic method" is built based on hydrology, aquatic biota (Tachamo-Shah et al., 2020) and cultural values (Sharma et al., 2020) collected in the period of 2016 – 2018 under the DJB (Digo Jal Bikas) project.	Both the Hydrological and Holistic methods estimate e-flows requirements to maintain the rivers in different management categories ranging from "pristine" to "highly modified". The Hydrological method generates "Environmental Flow Duration Curves" corresponding to six environmental management classes (EMCs) as described by Smakhtin and Anputha (Smakhtin and Anputhas, 2006), while the Holistic model defines only two management classes: "pristine" and "heavily modified EMCs represent prescribed or negotiated conditions under which a river ecosystem may be maintained following flow modification. The higher the EMC, the more water will need to be allocated for ecosystems and more flow variability needs to be preserved, or closer to natural pattern. In contrast, the lower the EMC, the greater the deviation from the natural state. The six EMCs - A, B, C, D, E, and F – classify rivers based on their ecological conditions. Category "A" rivers remain in a near-natural state with only minor modifications to in-stream and riparian habitats. In contrast, category "F" rivers are highly modified, one that have reached a critical level and the ecosystem has been completely altered, with an almost total loss of natural habitat and biota. In the worst-case scenario, basic ecosystem functions are destroyed and the changes become irreversible.	(International Water Management Institute 2019)

water and environment-related fields though not necessarily with direct experience in e-flows applications. Secondly, these stakeholders were approached through official channels to ensure their participation. As a result, the survey population comprised government officials, academicians, EIA practitioners, researchers, advocates, advisors, hydropower developers and donors. The survey remained open for approximately two months from December 2022 to January 2023, with three to four reminder rounds scheduled during the survey period.

In addition to the survey, five Key Informant Interviews (KIIs) were carried out at the provincial level with key personnel from relevant provincial governmental agencies in Surkhet, the capital city of Karnali Province. Moreover, nine focus group discussions (FGDs) were conducted in April 2023 using a structured questionnaire (Supplementary 2), with individuals of 5–11 representing fisher communities, Upper Karnali Hydropower Development Concern Group, Drinking Water User Group, Drinking Water Supply Management Group, Business and Market Management Committee/hotel owners, Livestock Management Group along the 25 km Karnali river stretch from Tallo Dungeshwor to Rakam Karnali to gather their responses. For better understanding and clarity of questions among the participants of the KIIs and FGDs, the surveyor translated the questions into the administrative language, i.e., "Nepali". This river stretch was selected because the 900 MW Upper Karnali Hydroelectric Project is licensed for its construction (Fig. 2). If the project proceeds, it will likely dewater a 52 km downstream section from the project site at Dab station.

The survey outcomes were evaluated on a 5-point scale ranging from 1 to 5 (very low to very high). This assessment measured participants' responses regarding the impacts of hydropower projects, awareness of e-flows, and barriers to implementing e-flows in their respective disciplines, while respondents' recommendations for mainstreaming e-flow assessments in the country were analyzed using a 5-point Likert scale.

3. Results and discussion

3.1. Overview of survey respondents

A total of 67 responses (61 %) were received during the survey period. The largest proportion of respondents were researchers, academicians and EIA practitioners (48 %), followed by government regulatory officials (33 %), developers (10 %) and donors (9 %) (Fig. 3). Among the respondents, 36 % were from government agencies, 21 % from NGOs, 10 % from universities, INGOs, and hydropower companies, 8 % were independent consultants and 5 % represented community-based organizations (CBOs). The high proportion of respondents representing academia, research and practitioners in such studies is common, as they are the primary groups involved in testing, modifying, and applying relevant methods. Government agencies, as the second-largest group, are key stakeholders responsible for formulating policies and regulating them based on the research outcomes.

3.2. Hydropower development and opportunities

The majority of respondents (76 %) perceive a strong potential for

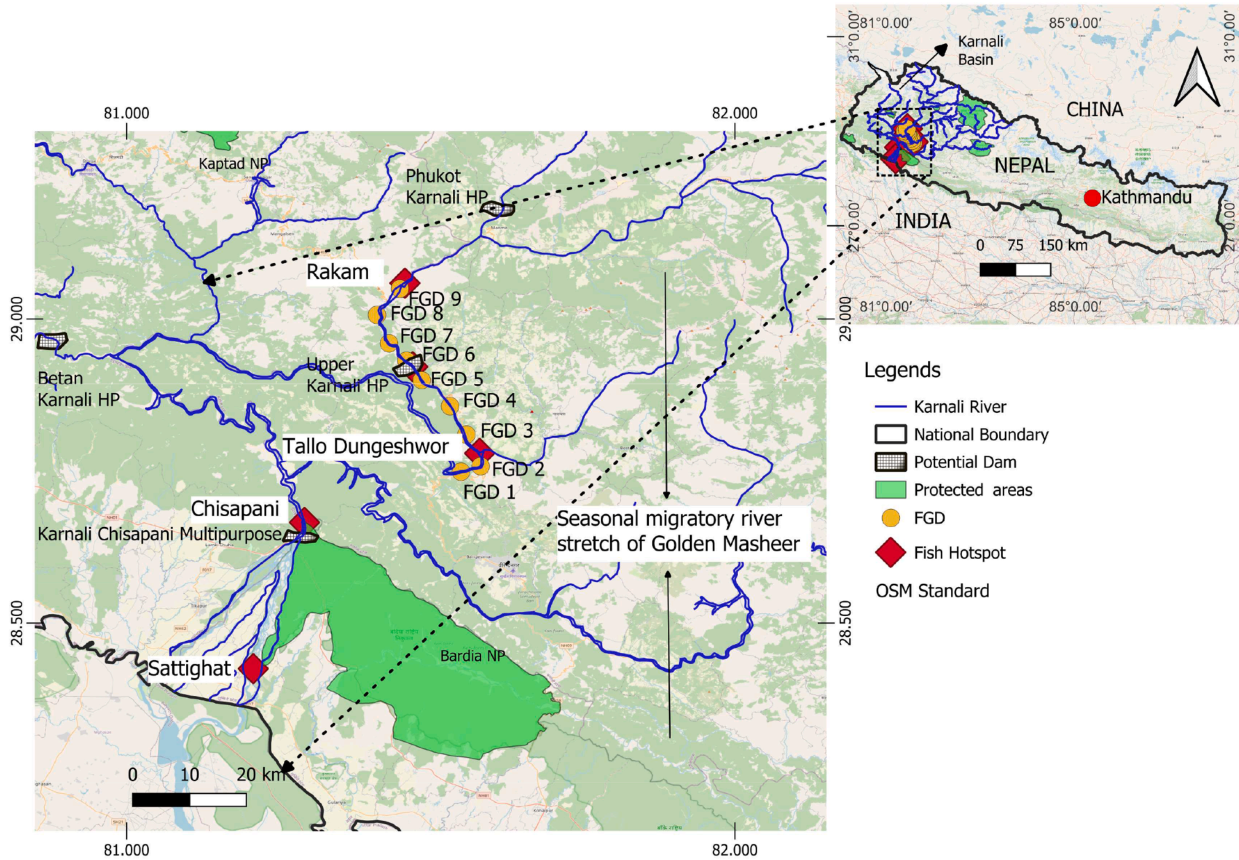

Fig. 2. Sites of fish hotspots in Karnali River and distribution of FGDs along the Karnali River. FGD represents focal group discussion, NP represents National Park.

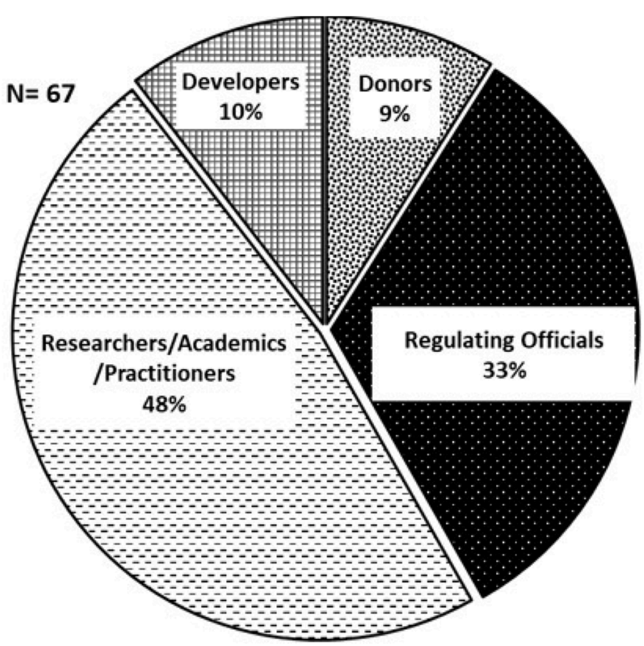

Fig. 3. Proportion of respondents with respect to their involvement and workspace (The figure is based on the respondents' responses; $N = 67$; current study).

hydropower development in the Karnali River Basin (Fig. 4). Notably, all respondents representing developers and over 80 % of government agency representatives concurred on the high potential for hydropower development. Researchers, academicians and practitioners had mixed responses of which about 13 % disagreed with the feasibility of hydropower development in the basin.

A significant proportion of respondents (88 %) believed that the hydropower development would contribute to other infrastructure development, such as road expansion and electrification that would greatly benefit the region (Fig. 5). Moreover, approximately 10 % of the respondents believed that hydropower development can also play a role in creating economic opportunities such as job placement. Across the country, hydropower is widely recognized for its socio-economic effects on local communities. According to 2020 data, the Karnali province had the lowest Human Development Index (HDI-0.538) in the country compared to the national average of 0.587. The province also had a poverty rate of 51.2 %, higher than the national rate of 28.6 % recorded in 2014 (Adhikari et al., 2023). As the province is the most food-insecure and poverty-ridden among others in the country, at least one or two family members from nearly every household (except for a few affluent families) have to work or seasonally migrate to India (Adhikari et al., 2023). This socioeconomic context likely explains why almost all FGDs participants, aside from fishermen emphasized that hydropower development would enhance infrastructure and generate employment opportunities in the basin and serve as a catalyst for the province's development. A regional study carried out by the Asian Development Bank (Asian Development Bank (ADB) 2020) showed that hydropower generation contributes to increased domestic incomes, poverty reduction, lower real domestic energy prices, and insurance against oil price increases. The economic growth of several countries, including Bhutan, Norway, the United States, and Canada, has been positively influenced by hydropower development (World Bank 2009). Properly designed and regulated multipurpose water infrastructure provides additional benefits including opportunities for irrigation, fisheries, and domestic and industrial water supply (Gonzalez et al., 2020; Wyrwoll and Grafton, 2022).

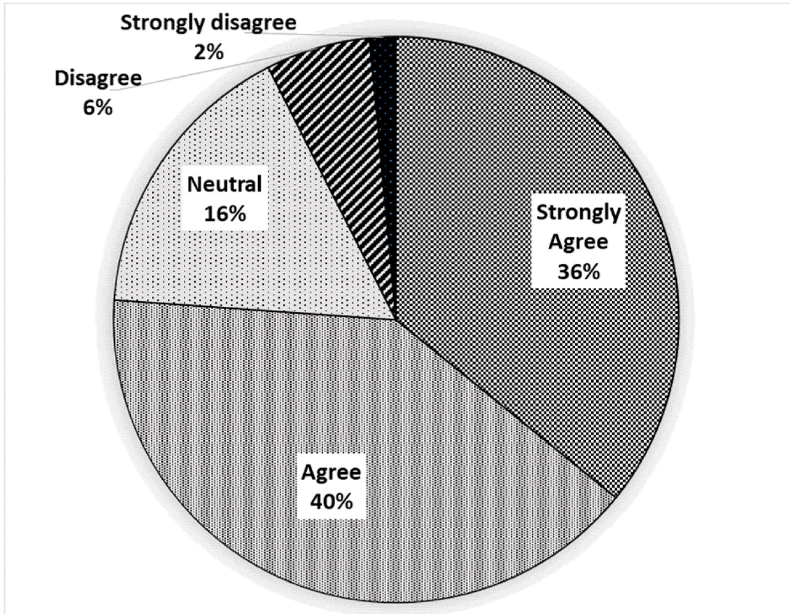

Fig. 4. Respondents' responses on the feasibility of hydropower development in the Karnali River Basin (The figure is based on the respondents' responses; $N = 67$; current study).

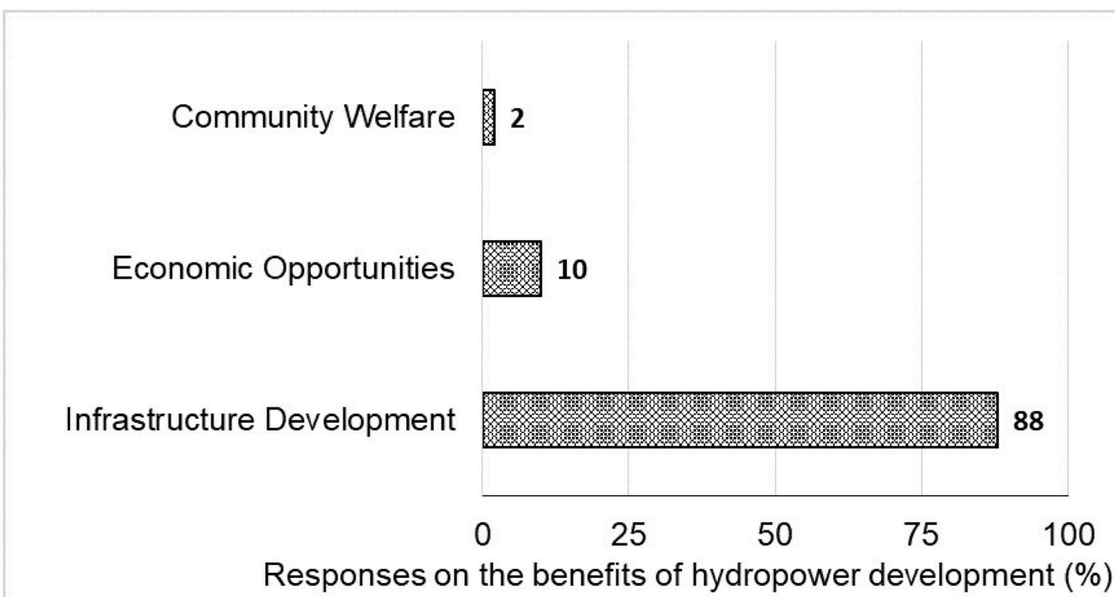

Fig. 5. Respondents' responses on the opportunities upon the development of hydropower (The figure is based on the respondents' responses; $N = 67$; current study).

3.3. Hydropower development and environmental challenges

Over 70 % of respondents reported that hydropower development contributes to the decline of aquatic biodiversity (e.g., fish diversity). Similarly, about 56 % of participants stated that hydropower projects lead to reduced river flows, while only a small portion of respondents (18 %) believed that hydropower development significantly affects water quality in rivers (Fig. 6). The negative consequences of hydropower projects were also strongly perceived by riparian communities, primarily those living near dewatered stretches and the dam site of the proposed Upper Karnali Hydroelectric Project. These findings align with the global reports, which revealed that the impacts of hydropower operations extend beyond aquatic ecosystems, significantly affecting terrestrial habitats and their associated biota (Jones and Bull, 2020). For example, a study on the Balbina hydroelectric dam in Brazil predicted that, after 26 years of operation, approximately 70 % of native medium-to-large vertebrate populations in the tropical Amazon rainforest would face local extinction (Benchimol and Peres, 2015). Habitat alteration and fragmentation remain major concerns as the dam operation disrupts the longitudinal connectivity of rivers hindering the natural movement of fish upstream and downstream (Benchimol and Peres, 2015; Zarf et al., 2019; Stoffels et al., 2022). This disruption leads to population isolation between the upstream and downstream of the dam; consequently, both populations are reduced and become more vulnerable to threats, such as inbreeding, and especially endemic species face an increased risk of extinction (Zarf et al., 2019). Many major river

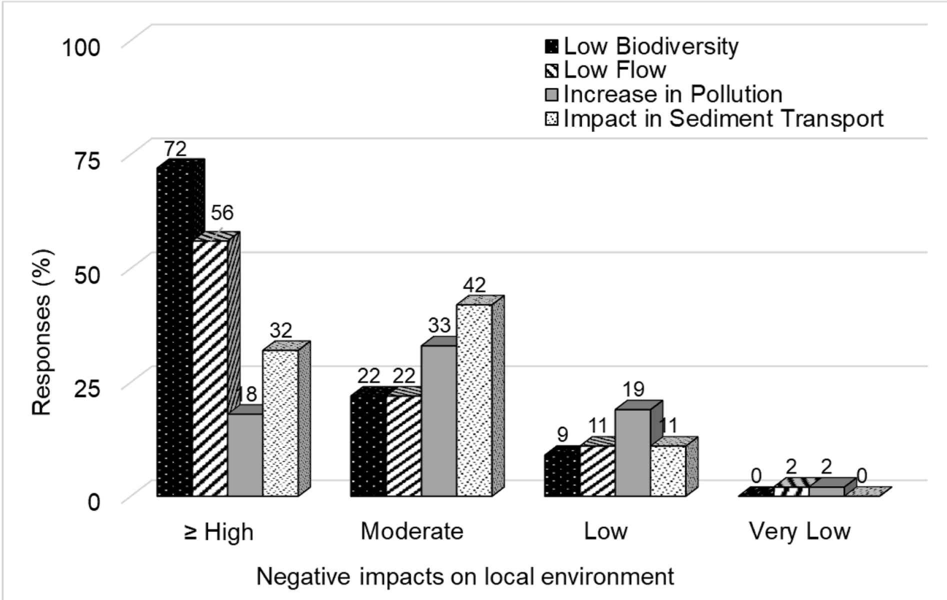

Fig. 6. Impacts of hydropower development on the local environment (Figure is based on the respondents' responses; $N = 67$, current study).

systems in Nepal, including the Karnali River, are home to endangered species such as Gangetic river dolphin (*Platanista gangetica*) and the Golden Mahseer (*Tor putitora*) (Tachamo Shah et al., 2019). The Gangetic river dolphin, exclusive to the Indian subcontinent, relies on deep-water channels for survival, while the Golden Mahseer depends on river connectivity for its seasonal migration (Shah et al., 2020).

The Karnali River is known for its fish diversity. The river supports numerous economically and ecologically important fish species, including Golden Masheer (*Tor putitora*), *Schizothorax richardsonii, Labeo angra, Labeo dero* and *Acrossocheilus hexagonolepis* (Grill et al., 2020). The river serves as a crucial spawning ground for Golden Masheer. During March and April, these fish migrate from downstream lowlands to mountainous areas at an elevation of up to 1200 m asl with juveniles returning to lower elevations between September and October (Tachamo Shah et al., 2019). Moreover, the Karnali River sustains hundreds of families whose livelihoods depend on capture fisheries from Rakam in mountainous areas to Kailali in lowland areas (Tachamo Shah, 2020). The main fish catch hotspots along the river are Rakam, Tallo Dungeshwor, Chisapani and Sattighat (Fig. 2). Many biologically diverse national parks are situated along the banks of the Karnali River, from its headwater to downstream areas. These include Dorphatan Hunting Reserve, Khaptad National Park, and Bardia National Park, the latter national park situated just below the proposed Karnali Chisapani Multipurpose project (10,800 MW).

3.4. Awareness on environmental flows

The academic literature contains limited studies specifically examining stakeholders' perceptions of environmental flows (e-flows) (Kosovac et al., 2023). Remarkably, most of these studies have been conducted in Australia (Mendham and Curtis, 2018; Syme et al., 1999), and the United States (Mott Lacroix et al., 2016). In the present study, awareness level on e-flows was found to be relatively high at the central level (48 %) compared to the provincial level. Nevertheless, all respondents believed that reduced discharge induced by hydropower operations leads to a decline in biodiversity in downstream stretches of the dam. Mendham and Curtis (Mendham and Curtis, 2018) reported that urban dwellers and field walkers had positive perceptions of e-flows in determining river values, while local water users expressed negative attitudes. In contrast, 100 % of the respondents in this study supported e-flows. Assessing public perceptions of e-flows is challenging, primarily due to a general lack of awareness and varying attitudes toward the concept, as noted by Mott Lacroix et al., (Mott Lacroix et al., 2016). A similar finding was observed in this study, where respondents employed in development sectors at the provincial level demonstrated a higher familiarity with e-flows, largely due to their participation in e-flows-related workshops and seminars.

Despite e-flows awareness among respondents, only 5 % (3 out of 67) were familiar with all four types of e-flows methods. Additionally, 10 % of respondents were unfamiliar with any e-flows methods while 48 %, 16 %, 14 % and 12 % of respondents were familiar only with hydrological, hydraulic, habitat simulation and holistic methods, respectively (Fig. 7A). According to the responses, hydrological methods were the most commonly applied in hydropower projects (60 %), followed by holistic methods, 10 % minimum discharge and hydraulic rating methods (Fig. 7B). Meanwhile, 13 % of respondents were uncertain about the types of e-flow methods used in hydropower development projects. Although familiarity with e-flows assessment was relatively high among regulating officials, particularly government agency representatives (18 %), academicians, researchers and EIA practitioners were more equipped with e-flow assessment techniques (22 %).

In contrast, very few individuals representing regulating bodies (4), developers (2), and donors (1) had knowledge of e-flow estimation methods, and none had previously applied them in any project except for two government officials (Fig. 8). Furthermore, the majority of respondents representing Community-Based Organizations (CBOs) and some Non-Governmental Organizations (NGOs) were unfamiliar with the concept of e-flows.

The focus group discussions (FGDs) conducted along the Karnali River revealed significant spatial variation in awareness on e-flows. For example, the riparian communities in a potential dewatered zone and dam site (the proposed Upper Karnali Hydroelectric Project Dam at Dab station in Karnali) were aware of the 10 % minimum river flow and its importance for the aquatic environment and people's livelihoods while riparian communities in upstream of the proposed Upper Karnali Hydroelectric Project Dam, i.e., at Rakam, Karnali were unfamiliar with the e-flows concept. The awareness of e-flows among these communities in the project area (i.e., from the impoundment zone to the dewatered zone of the proposed Upper Karnali Hydroelectric Project) was mainly because of sensitization activities on the benefits of environmental flows carried out by the project's staff. Therefore, regular awareness campaigns can bring pro-environmental values among the concerned

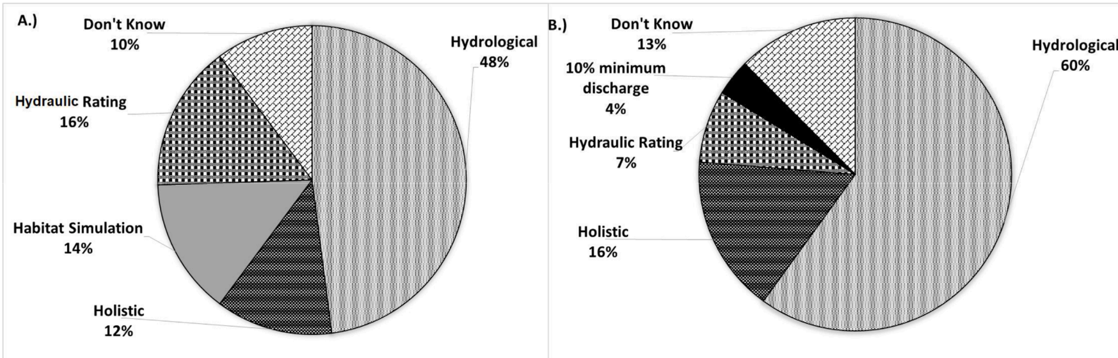

Fig. 7. Responses heard about hydrological, habitat simulation, hydraulic, and holistic e-flow calculation methods (A.) and e-flow calculation methods used in Hydropower projects (B.). The same texture patterns have been followed in both figures.

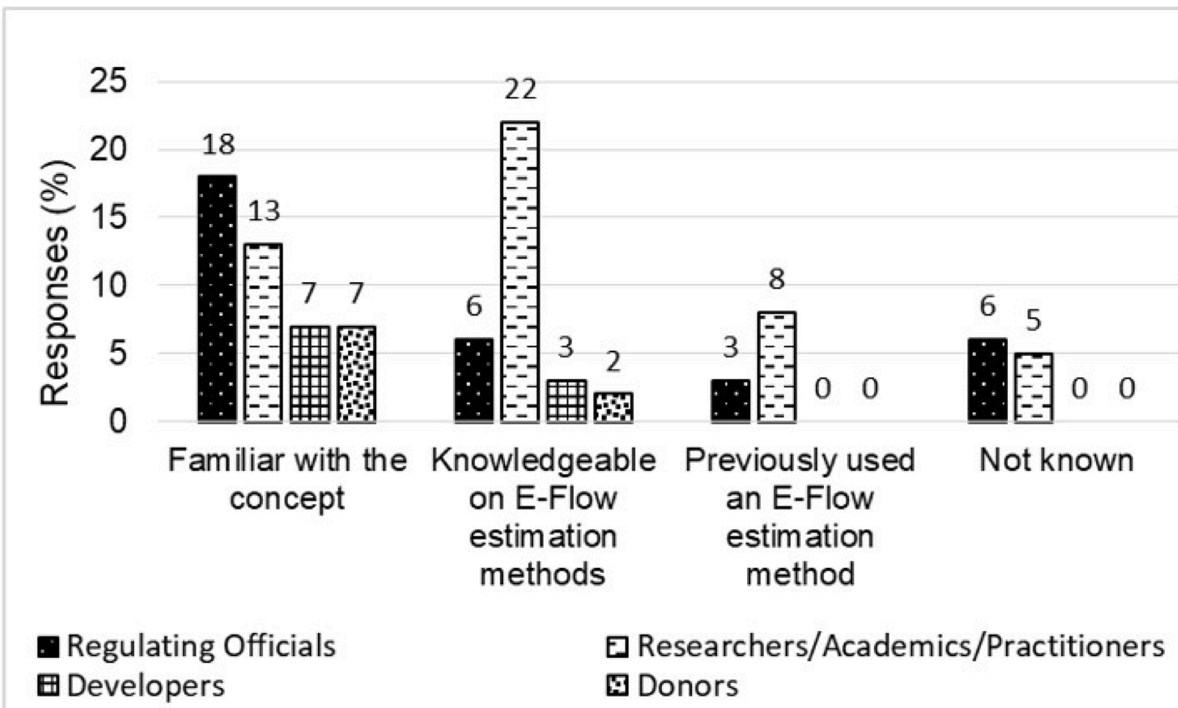

Fig. 8. Responses from participants representing government agencies, academic institutions, NGOs, CBOs, hydropower developers, and donors across e-flow concepts, estimation methods, and practices in hydropower projects.

stakeholders that lead to a favorable judgment of the benefits of e-flows at a project site [*sensu* (Mendham and Curtis, 2018)]. Rakam-Karnali is the hotspot of snow trout (*Schizothorax sp.*). Dozens of people engage in fishing each day in this stretch. Due to this resource, the area is mainly inhabited by the fisher (locally called Majhi) community. If environmental flows are not incorporated into upstream hydroelectric projects such as Phukot Karnali (480) and Mugu Karnali (1902 MW), the livelihoods of the fisher community are likely to be impacted severely.

3.5. Barriers to prescribing e-flows in water resources management

A large proportion of respondents (87 %) highlighted that the lack of follow-up of environmental impact assessment (EIA) and initial environmental examination (IEE) outcomes has contributed to low practices of e-flows implementation in hydropower development (Fig. 9). Although EIA studies identify negative impacts of dams on riverine ecosystems (Thanju, 2007) and recommend the implementation of e-flows in hydropower development, these measures have not been adequately addressed (Agrawal et al., 2010; Bhatt and Khanal, 2009). This shortfall is primarily attributed to the absence of robust regulatory mechanisms and oversight institutions. Seventy-four percent of the respondents noted that the absence or inadequacy of a regulatory body responsible for enforcing environmental protection measures plays a crucial role in the low compliance rates. Lack of monitoring by the regulatory bodies might be due to their limited human resource and knowledge of e-flow methodology (Fig. 8). Effective inter-departmental coordination (e.g., Environmental Standards and Monitoring Unit, Environmental Impact Studies Unit, Project Facilitation Unit) within the Ministry of Forests and Environment would be important for accountability and incentives for project developers to adhere to EIA and IEE recommendations.

Sixty-seven percent of the respondents identified the absence of supportive policies as a significant contributing factor. When there is a lack of policies that promote and enforce environmental protection and sustainable practices, project developers may prioritize economic interests over environmental concerns. While the Environment Protection

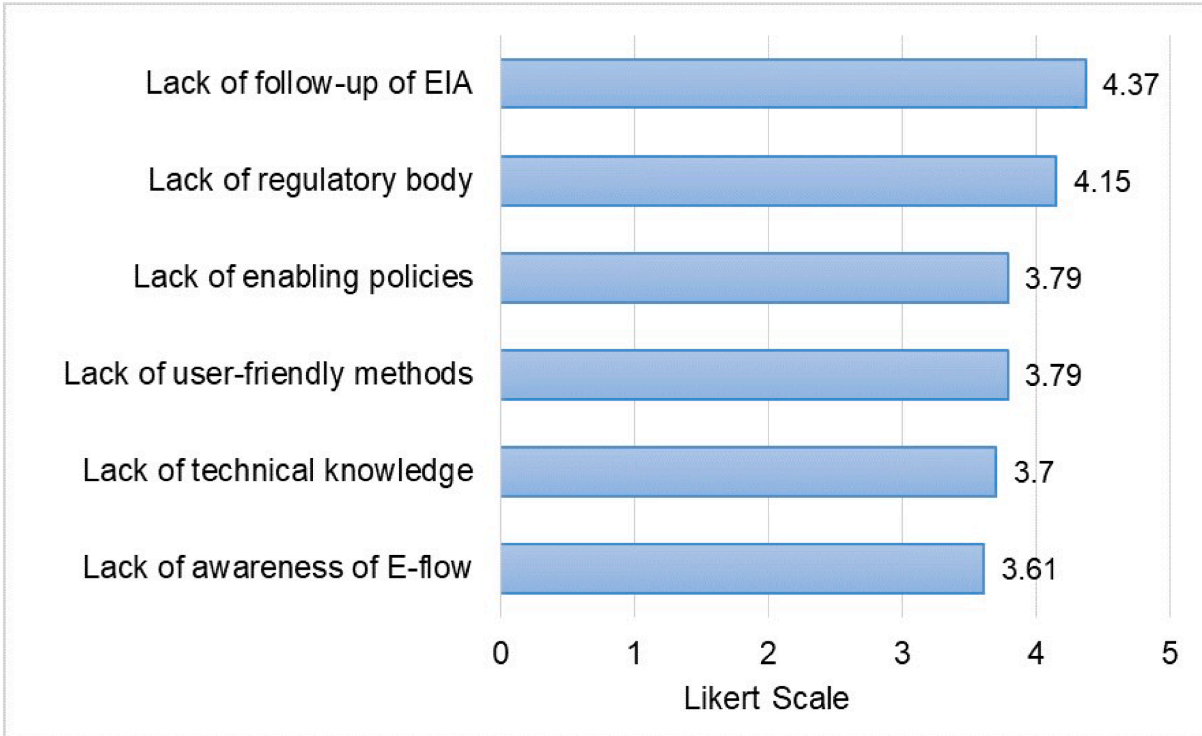

Fig. 9. The Likert scale of responses from the respondents on major barriers to mainstreaming environmental flows implementation.

Act 1996 had provisions for fine of up to NPR 1,00,000 which was increased up to NPR 5,00,000 (approximately 3650 USD) by the Environment Protection Act 2019 (Government of Nepal (GoN) 2019) for failing to implement mitigation measures, enforcement remains weak. Similar to other Asian countries, Nepal faces challenges in monitoring and penalizing non-compliance, resulting in persistent environmental negligence in hydropower projects (Aryal et al., 2020)

This study findings also suggest that the absence of a regulatory body, the lack of a clearly defined monitoring authority, insufficient technical knowledge, and the unavailability of user-friendly methods are substantial barriers to effective environmental protection in Nepal (Fig. 9). Similarly, a lack of awareness of e-flow benefits among the stakeholders is another barrier for e-flows implementation and regulation in the country (Ghimire et al., 2021).

The other pertinent issue underlying the ineffective implementation of e-flows in the country is the lack of skilled human resources. Only 9 % of respondents had applied e-flow estimation methods in their previous works and only one respondent was highly skilled in estimating e-flows. Furthermore, most e-flows methods (except Western Nepal Environmental Flow Calculator (WENEFC) (International Water Management Institute 2019)) have been formulated in other countries and used in the country without modification, leaving doubts on their effectiveness (Tennant, 1976; Hughes and Hannart, 2003; Richter et al., 1997). The WENEFC (International Water Management Institute 2019), developed specifically for the Western river systems of Nepal (Table 2) with contributions from local stakeholders, calculates e-flow values to sustain river ecosystems while meeting people's needs. Therefore, mainstreaming such holistic methods, developed based on the hydrological, ecological and socio-cultural data from the local context and applied within the same environment, ensures their relevance and effectiveness on the ground. However, the application of WENEFC depends on the accessibility to practitioners, compatibility with other basins, and adaptability among users. Moreover, incorporating multiple e-flow classes aligned with the already established "Environmental Management Classes (EMCs)" (Smakhtin and Eriyagama, 2008) may be necessary for its practical uses. In its current form, the holistic approach built in the WENEFC provides only two classes: Class A (Minor modifications) and Class B (Largely Modified). Similarly, a lack of advanced technical knowledge and institutional capabilities continue to hinder e-flows implementation in water resources development. Other barriers include the absence of a regular budget for improving and contextualizing e-flows methods in the areas of implementation.

3.6. *Recommendations for mainstreaming the environmental flow*

Approximately 80 % of the respondents believed that raising awareness and building the capacity of stakeholders could enhance the implementation of e-flows in the country (Fig. 10). However, the government's effort to maintain e-flows may have been hindered by a limited country-specific technical knowledge on the subject. Strengthening the capacities of representatives from various organizations, including developers, EIA practitioners, researchers, donors and government agencies, on e-flow methodologies could help integrate e-flows into hydropower development. This should be followed by regular assessments, refinement of strategies over time, and improved regulation and monitoring e-flows in hydropower projects. Donor engagement in such capacity-building initiatives would further enhance awareness of e-flow assessments and support its implementation.

Equally important is the development of user-friendly e-flows calculation methods that are accessible, easy to operate, and capable of producing robust outcomes. Additionally, establishing adequate policies, and enforcing strict measures are essential to promoting e-flows implementation in hydropower projects in Nepal. Several legal frameworks, such as the Aquatic Animal Protection Act (1960), Water Resources Act (1992), Hydropower Development Policy (2001), Water Resources Strategy (2002), National Wetland Policy (2012), Environmental Protection Act 2019, Environmental Protection Rules 2020, and National Water Resources Policy (2020) aim to harness water resources while maintaining ecological integrity. However, ensuring energy production while simultaneously achieving ecological balance and meeting societal needs remains a challenge due to weak law enforcement.

The availability of modern equipment and technology for collecting

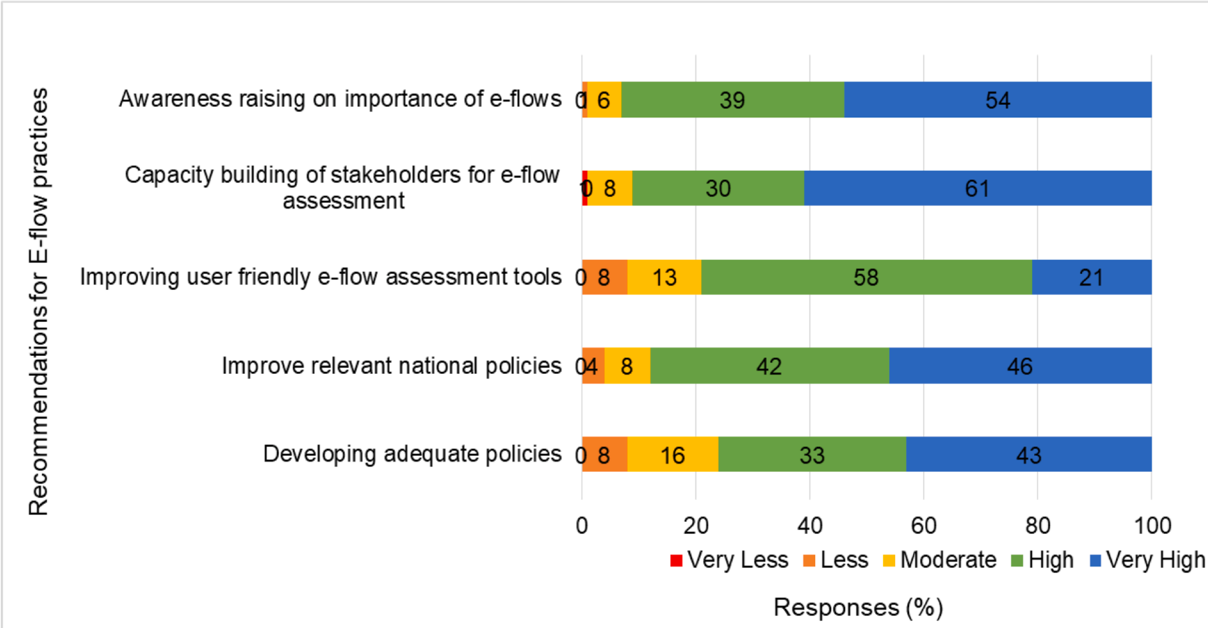

Fig. 10. Measures necessary for the proper implementation of e-flows in Nepal.

time series hydrological data, strong compliance monitoring mechanisms, stakeholder capacity building, and enhancing technical and scientific knowledge could support in mainstreaming e-flows in Nepal. Inter-departmental collaboration within government institutions also plays a critical role in acquiring and utilizing data effectively. Furthermore, socio-political arrangements and hydrological uncertainties must be considered for sustainable e-flows management in the long run (Rauniar, 2022). Basin-level dialogues among local and regional water user groups, riparian communities reliant on instream resources and other beneficiaries of the water resources are necessary for holistic decision-making (Ghimire et al., 2021). Additionally, securing regular funding is critical for advancing e-flows programs and ensuring their integration into national water management frameworks. Independent third-party auditing of environmental impact assessment (EIA) monitoring could further enforce the implementation of e-flows in hydropower projects (World Bank Group, 2018). While Nepal has adopted Integrated Water Resource Management (IWRM) as a framework for water resources development, it has not sufficiently prioritized the environmental and social components of IWRM. Integrating e-flow assessments into water resource planning could be a key approach to achieving sustainable water resource development. This, in turn, would help Nepal meet its Sustainable Development Goals (SDGs) particularly SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), SDG 14 (life below water) and SDG 15 (life on land).

However, the study has some limitations. The findings are based on the subjective perceptions of respondents, which may introduce some bias. In addition, the sample size of 67 respondents, though diverse, may not fully capture national-level perspectives. Moreover, the focus group discussions were conducted in the selected lower stretch of the Karnali River basin, which may not reflect the full range of hydropower and e-flow challenges in other regions of Nepal.

4. Conclusion

The implementation of environmental flows (e-flows) in Nepal is still in its early stages and requires considerable attention to ensure the sustainable development of water resources, while also improving the health of riparian ecosystems and conserving biodiversity. Hydropower development contributes to socio-economic and infrastructure development, but it also poses serious challenges by degrading river health, impeding fish migration, and causing biodiversity loss. The study also indicates that people's awareness of the e-flows concept depends largely on an individual's exposure to subject-specific workshops and activities. Therefore, building the capacity of stakeholders, including government agencies, water managers, EIA practitioners, private sectors, donors and local advocates, is equally important to enhance awareness and expertise in e-flows management. Although the government has introduced e-flows provisions, their effectiveness depends on the establishment of strong regulatory frameworks, strict monitoring, enforcement mechanisms, and compliance measures to safeguard ecosystems and biodiversity. Similarly, it is crucial to adapt e-flows assessment tools to Nepal's diverse hydrological, ecological, socio-economic and cultural contexts. Achieving a balance between water resource development and environmental sustainability is essential for Nepal's long-term ecological and socio-economic resilience, as well as achieving the SDGs. Moreover, future studies should integrate transboundary water-sharing values into environmental flow assessments, as Nepal shares major watersheds with neighboring countries, China and India. This approach will promote regional cooperation, ensure sustainable water use, and help maintain ecological integrity across borders.

CRediT authorship contribution statement

Ram Devi Tachamo-Shah: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Santosh Nepal:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization. **Deep Narayan Shah:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Conceptualization. **Nishadi Eriyagama:** Writing – review & editing, Writing – original draft, Visualization, Validation, Conceptualization.

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2025.101211.

Data availability

Data will be made available on request.

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