

Article

Environmental Flows Assessment in Nepal: The Case of Kaligandaki River

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Abstract: Environmental flow assessments (e-flows) are relatively new practices, especially in developing countries such as Nepal. This study presents a comprehensive analysis of the influence of hydrologically based e-flow methods in the natural flow regime. The study used different hydrological-based methods, namely, the Global Environmental Flow Calculator, the Tennant method, the flow duration curve method, the dynamic method, the mean annual flow method, and the annual distribution method to allocate e-flows in the Kaligandaki River. The most common practice for setting e-flows consists of allocating a specific percentage of mean annual flow or portion of flow derived from specific percentiles of the flow duration curve. However, e-flow releases should mimic the river's intra-annual variability to meet the specific ecological function at different river trophic levels and in different periods over a year covering biotas life stages. The suitability of the methods was analyzed using the Indicators of Hydrological Alterations and e-flows components. The annual distribution method and the 30%Q-D (30% of daily discharge) methods showed a low alteration at the five global indexes for each group of Indicators of Hydrological Alterations and e-flows components, which allowed us to conclude that these methods are superior to the other methods. Hence, the study results concluded that 30%Q-D and annual distribution methods are more suitable for the e-flows implementation to meet the riverine ecosystem's annual dynamic demand to maintain the river's health. This case study can be used as a guideline to allocate e-flows in the Kaligandaki River, particularly for small hydropower plants.

Keywords: dynamic flow releases; flow regime; hydrological methods; Indicators of Hydrological Alteration; river health

1. Introduction

1.1. Overview of E-Flow Concept

Climate change, rapid globalization, economic boost, and ever-increasing populations demand better management of water resources. To meet humankind's demands (i.e., energy, water), many water conservancy and hydropower projects have been built [1]. Several hydropower plants are under construction or planned to be constructed, which will modify the rivers' natural flow regime either

through impoundments such as dams and barrages or through diversion work for agriculture or urban supplies [2]. These projects contribute to tackling the climate change effect (drought, floods) and improve the living standard of citizens (rent standards). However, its adverse effects, such as reducing total flow discharge left to the river, changing the seasonal flow regime [3,4], altering the magnitude and frequency of floods, and modifying the groundwater table are a severe threat to the aquatic ecosystem existence [5,6]. Most rivers with dams and diversion projects are at the ecological tipping point, which means act now or face the projects' worst effects soon. Hence, along with humankind's benefits, it is required to protect the rivers, natural lakes, and groundwater of the watershed by mitigating the riverine ecosystem [7].

The escalating hydrological alterations of the rivers flow regime, and its resulting severe impacts on the riverine ecosystem's health is recognized globally [8–10]. With the advent of growing public consciousness in the river health and its hydrological alteration causing adverse impacts, river scientists developed the science of environmental flows (e-flows) assessments, which aid in determining the quality and quantity of water required for the protection of the riverine ecosystem and its inhabitants. The US clean water act 1977, 1992 European Commission (EC), Habitat Directive, and 2000 EC Water Framework Directives are examples that stressed mandatory river restoration to improve rivers' ecological status. The Water Sustainability Act (2016) mandated that streamflow should not reduce below the environmental flow needed due to groundwater pumping in British Columbia and Canada. Environmental flow has been mandated in British Columbia, Canada, and California, USA [11]. An "Instream Flow Requirement (IFR)," "environmental flows," "Environmental Flows Requirement (EFR)," or "environmental water demand (EWD)" are used as interchangeable terminology for the e-flows [2]. E-flows represent the flow regime provided within a river downstream to maintain a certain acceptable river health level and are widely used as environmental protection measures in many water conservancies projects [12,13]. E-flows is defined as "*the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being,*" according to the Brisbane Declaration [14]. The process of defining the e-flows is known as "environmental flow assessment (EFA)" [15]. E-flows represent the water needed for the river ecosystem. However, there are other demands as well, such as residential, agriculture, and farming. Hence, all respective sectors' demand should be considered to understand the relationship between water availability and water stress on the river ecosystem. For instance, Xu et al. [16] integrated the e-flow requirement in water-stress impact analysis to inform energy system deployment. This study did not consider any water needs except for hydropower production. All of the basin's existing facilities' water needs should be integrated to conduct water-stress analysis, giving us an idea about the basin's energy system deployment. Groundwater plays a vital role in river hydrology and ecology at various scales (spatial and temporal), evaluating the spatial and temporal pumping effects on streamflow depletion while allocating environmental flows [17,18]. Gleeson and Richter [18] suggested that "high levels of ecological protection will be provided if groundwater pumping decreases monthly natural baseflow by less than 10% through time". However, the discussed e-flows methodologies do not consider the impact of groundwater pumping. The study recommends integrating the impact of groundwater pumping and the impact of water infrastructure on environmental flows.

Environmental flow methodologies stem from a need to conserve mostly rivers and wetlands sustainably with the appropriate ecological balance in the water system close to the natural flow regime. This concern led to the development of different approaches in the environmental flows' methodologies worldwide. Tharme [8] reviewed more than 200 methodologies spread across different geographical spectra. Though all of these methodologies, in principle, have the same goal to achieve a suitable environmental flow regime of water bodies, they differ in their working principle and assumptions made during derivation. These vast methodologies can be classified into four major categories: (1) hydrological, (2) hydraulic rating, (3) habitat simulation, and (4) holistic methodologies. The first two categories, hydrological and hydraulic rating, are based on the assumption that water bodies' habitats/ecosystem functions (e.g., rivers) degrade with reducing water availability in the

river. Whereas, habitat simulation assumes an “optimal” flow in the river, sustaining the river ecology in balance [9,19]. Holistic methods are more comprehensive methods with environmental flows designed to mimic the natural hydrograph [20]. Table 1 shows a short overview of all types of methods. The different factors, namely, types of the river (e.g., perennial, seasonal, high base flow, flashy); ecological importance of the river; stakeholders involved; cost; and difficulty of obtaining data decide the preference of the EFA methods [21]. For brevity, the concepts and details of these methods are described in the literature [19,20,22–25].

Table 1. Selection criteria for different environmental flow calculation methodologies [26].

Method Category	Resolution Level	Ecosystem	Time	Cost
Hydrologic	Very Low/Low	River	Short	Less
Hydraulic rating	Low	River	Short/Long	Less/Medium
Habit simulation	Medium/High	River	Medium/Long	Medium/High
Holistic	High	Wetland, floodplains,	Long	High

Hydrological methods use historical flow data records (e.g., daily, monthly, seasonal, yearly flow) to recommend an e-flows setting for maintaining the desired level of river health [24]. Rather than focusing on the optimized environment for single species, this method encompasses the conservation of rivers’ overall ecological integrity. The hydrological methods assume that there exists a relationship between flow parameters and biological attributes [27]. Based on this, different parameters are developed to optimize the flow regime. However, hydrological methods have some limitations. They can be used only in gauged catchments, are sensitive to hydrological data, and assume that all the aquatic organisms need the same quantity of water for survival. Due to its easiness of application, rapid assessment, low cost, and fewer field visits with most of the data readily arrived or can be simulated; hydrological methods are widely used to calculate environmental flow [28]. About 30% of all methods are hydrological-based [29]. Most of the preliminary and planning studies’ hydrological methods are used [30]. Suwal et al. [31] used the desktop hydrological method “Global Environmental Flow Calculator” (GEFC) to calculate the e-flow for different classes. Pastor et al. [32] recommended the suitability of the Variable Monthly Flow (VMF) and Tessman methods, especially for the variable flow regimes river.

1.2. Environmental Flows Practices in Nepal

The world is focusing and giving prime importance to the ecological impact assessment of water-related projects like hydropower and developing a robust e-flows setting methodology to ensure rivers’ ecological integrity [27,33,34]. The concept of e-flows is burgeoning on a global scale. However, in Nepal, the e-flows concept is still in its infancy as investors and the government are not serious about the rivers’ e-flows requirements while constructing water conservancy projects on the rivers in Nepal. Many hydropower projects (storage, run of the river, and peaking run of the river) are at the construction phase. Most of the projects are located on most of Nepal’s major rivers’, namely in Kaligandaki, Karnali, and Mahakali. Developed countries have used different advanced and robust methodological approaches for e-flows regulation. However, developing nations like Nepal usually use hydrological methods. Though hydropower development goes back a century, environmental flow concern was not significant until the Water Resource Act, 1992 in Nepal. This act gave the basic idea about the “environmental study” but did not encompass the broader environmental flows aspect. The Environmental Protection Act (EPA), 1997, was the turning point for e-flows in Nepal as it gave basic guidelines and highlighted the need for Initial Environmental Examination (IEE) and Environmental Impact Assessment (EIA) based on the installed capacity of projects. The EPA made the Environmental Protection Rules (EPR, 1997), making it mandatory to conduct an EIA for projects above 50 MW, and an IEE study for projects below 50 MW [35]. The introduction of the Hydropower Development Policy, 2001, became the paradigm shift in the e-flows setting in Nepal

as it exclusively defined the minimum flow requirements for hydropower projects built onwards. Ecological, downstream, or environmental flows are the terms used in Nepal for the e-flows. The policy stated that “Provision should be made to release such quantum of water which is higher of either at least 10% of the minimum monthly average discharge of the river/stream or the minimum required quantum as identified in the environmental impact assessment study report” [35]. The working Policy for Construction and Operation of Physical Infrastructure within Protected Area (2009) further defined different provisions of e-flows that is: If the headworks is within the conservation areas, at least 50% of the monthly flow is considered as e-flows and if the headworks are not within conservation areas, but the downstream flow through the conservation areas, at least 10% of the monthly flow is considered as e-flows [35]. With the support of the International Water Management Institute (IWMI) and the World-Wide Fund for Nature (WWF), e-flows assessment in Nepal is undergoing in many rivers [36,37]. About 50% of all large rivers are affected by dam construction. Studies have identified that cold-water fish in Nepal are threatened due to block connectivity by dam blockages of hydropower projects [38]. Snow trout and gold mahseer are critically endangered fish species, and dark mahseer and *Gangetic ailia* are the vulnerable fish species according to the International Union for Conservation of Nature (IUCN).

Furthermore, the irrigation policy (2014) [39] gave the working direction and decided to use only the residual water for irrigation purposes after maintaining the minimum required water flow in the river and creeks. During the last two decades, many hydropower projects had been constructed. More projects are in the construction phase and the pipeline [40]. The EIA reports show the requirement of e-flows in the projects; however, due to a lack of monitoring resources, none of Nepal’s projects has been following the policy regarding the e-flows implementation, which is a severe threat to the downstream ecosystem of the projects. For instance, the Modi River did not get environmental flows as prescribed in EIA and IEE reports except for the wet season [41,42].

The case study on the environmental flow assessment discussed in this paper is located in Nepal’s Himalayan region. Table 1 shows that hydrological methods are best suited for Nepal on the primary investigation of e-flows. The main objectives of the present study are: (i) study different existing hydrological e-flow methods (EFMs) and allocate e-flows using six different e-flow methods; (ii) comparison of 6 EFMs; (iii) compute flow alteration using the Indicators of Hydrological Alterations (IHA) indicators and e-flows components (EFC) and application of global indexes; and (iv) to suggest better e-flows assessment methods (hydrological). The Kaligandaki River is considered as a case study for this investigation. The study is organized as follows: Section 2 presents details about the study area and applied methodologies. Section 3 shows the main results of the study. The discussion and conclusion are developed in Sections 4 and 5, respectively.

2. Materials and Method

2.1. Study Area

Kaligandaki is one of Nepal’s major rivers and the Narayani River (Figure 1). Narayani River joins the Ganges River in India as a left-bank tributary, eventually draining at the Bay of Bengal.

This paper’s study station is Kotagaon Shringe hydrometric station located at 27°45′00″N latitude and 84°20′50″E longitude at an elevation of 198 m [6]. The station lies downstream of the powerhouses of the Kaligandaki-A hydropower station. The daily flow values recorded at the Kotagaon station were obtained from the Department of Hydrology and Meteorology (DHM), Nepal (<http://dhm.gov.np/>). The mean daily flows data from the year 1964–2015 were used in the study. The details of the Kaligandaki River are shown in Table 2. These flow values were processed in MS-Excel.

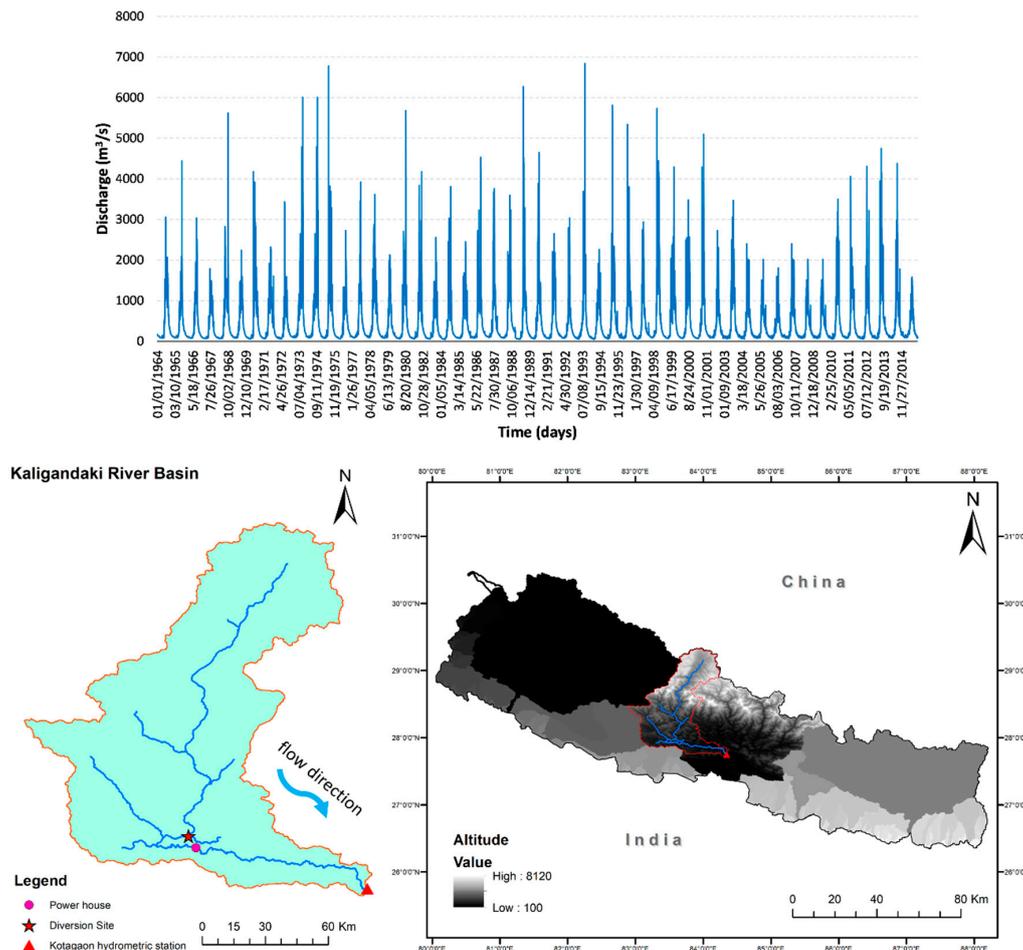


Figure 1. Hydropower and hydrometric station locations within the Kaligandaki River Basin, Nepal. The upper figure shows the mean daily time series of flow discharge from the year 1964–2015.

Table 2. Flow data and watershed description of Kaligandaki River, Nepal.

Name	Details
Elevation	190 m to 8168 m
Total catchment area	11,851 km ²
Location	82°52.8' E to 84°26.3' E, 27°43.2' N to 29°19.8' N
Mean annual precipitation	1396 mm
Flow data Series	1 January 1964–31 December 2015
Min flow (m ³ /s)	46
Mean flow (m ³ /s)	449.7
Max flow (m ³ /s)	6840
Min average monthly flow (m ³ /s)	90
10% of min average monthly flow (m ³ /s)	9

2.2. Methodology

In this study, six different hydrologic-based EFA methods were used to evaluate e-flows in the Kaligandaki River and later compared its effectiveness and influence on the natural flow regime using IHA indicators. The leading cause of using hydrological methods is the lack of ecological information of the basin, which is a must in other advanced methods, such as holistic habitat simulation methods. The figurative workflow of the study is shown in Figure 2. The key features of the used methods are discussed in the following sections.

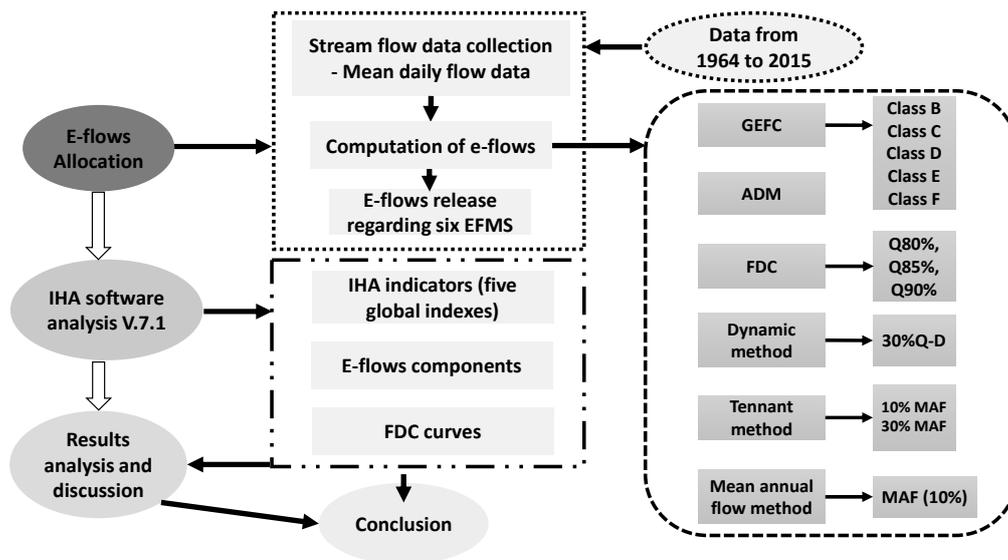


Figure 2. The flow chart shows the main steps and e-flow methods applied in this study.

2.2.1. Annual Distribution Method

The Annual Distribution Method (ADM) method is based on the mean ratio index, a ratio between annual average runoff and minimum annual average runoff. The ADM assumes that the minimum monthly average runoff of rivers could meet the essential water needs to maintain essential ecological, environmental function, give a favourable environment for the survival of the aquatic organism and riverine ecosystem will not suffer severe irreversible damage; however, it cannot reflect the hydrological characteristics of the river. Nevertheless, for many years, the average monthly discharge process can better reflect the overall historical river discharge process, such as timing, duration, frequency, and flow rate change. The mean ratio index is determined and quantified in the same period. According to the long series data of the natural average monthly flow of hydrological station, the average annual discharge \bar{Q} and the minimum annual discharge \bar{Q}_{\min} are calculated respectively [43]. The calculation formulas are given below:

$$\bar{Q} = \frac{1}{12} \sum_{i=1}^{12} \bar{q}_i \quad (1)$$

$$\bar{q}_i = \frac{1}{n} \sum_{j=1}^{12} q_{ij} \quad (2)$$

$$\bar{Q}_{\min} = \frac{1}{12} \sum_{i=1}^{12} q_{\min(i)} \quad (3)$$

$$q_{\min(i)} = \min(q_{ij}), j = 1, 2, \dots, n \quad (4)$$

where \bar{q}_i is the average monthly discharge of i th month during series of n years (m^3/s); $q_{\min(i)}$ is the minimum monthly discharge of i th month for n years (m^3/s); q_{ij} is the average discharge of i th month j th year; n is the number of years data available.

Calculate the mean ratio index (η) using an annual average discharge (\bar{Q}) and minimum annual average discharge (\bar{Q}_{\min}) at the same time.

$$\eta = \frac{\bar{Q}_{\min}}{\bar{Q}} \quad (5)$$

$$Q_i = \bar{q}_i \times \eta \quad (6)$$

Calculate the basic ecological flow for each month (Q_i) using Equation (6), where i is the month, i.e., $i = 1, 2-12$. The ADM method calculates monthly environmental flow; however, we needed daily flow for a year to compute IHA flow alteration. The study used Equation (7) to convert monthly environmental flow into daily flow [44].

$$Q_{env,j}^i = \frac{Q_{n,j}^i}{Q_n^i} \times Q_{env}^i \quad (7)$$

where $Q_{env,j}^i$ is the minimum environmental flow on the j th day of the i th month, $Q_{n,j}^i$ is the natural flow on the j th day of the i th month, Q_n^i is the average value of the natural flow of the i th month, and Q_{env}^i is the minimum environmental flow of the i th month.

2.2.2. Global Environmental Flow Calculator

The study used the “Global Environmental Flow Calculator” (GEFC) software [13] to calculate the environmental flow of different Environmental Management Classes (EMC). The GEFC software implements the “FDC Shifting” method. The details about the software are described in Smakhtin and Eriyagama [13]. The method describes ‘Environmental Management Classes’ (EMC). Table 3 shows the details about EMC and its corresponding ecological description with a management perspective. It classified EMC into six classes giving six similar environmental flow levels to each class. The software gives the percentage of mean annual flow (MAF) in each EMC. The study considers only EMC from B to F.

Table 3. Description of Environmental Management Classes (EMC) used in the Global Environmental Flow Calculator [2,13].

EMC	Most likely Ecological Condition	Management Perspective
A (Natural)	Same as natural rivers with insignificant modification of instream and riparian habitat	Protected rivers and basins. Reserves and national parks. No new water projects (dams, diversions, etc.) allowed.
B (Slightly modified)	Largely intact biodiversity and habitats despite anthropogenic activities (dam, diversion, basin modifications)	Water supply schemes or irrigation development present and/or allowed.
C (Moderately modified)	The biota’s habitats and movement have been impacted, but essential ecosystem functions are still unmodified; some sensitive species are vanished and/or reduced in extent; alien species survived.	Multiple disturbances (for instance, dams, diversions, habitat modification, and reduced water quality) related to the need for socio-economic development
D (Largely modified)	Substantial changes in natural habitat, biota, and essential ecosystem functions have occurred; a lower than expected species richness; the much-lowered presence of intolerant species; alien species prevail.	Significant and precise visible disturbances (such as dams, diversions, transfers, habitat modification, and water quality degradation) associated with basin and water resources development
E (Seriously modified)	Habitat diversity and availability have declined; species richness is strikingly lower than expected; only tolerant species remain; indigenous species can no longer breed; alien species have invaded the ecosystem.	High human population density and extensive water resources exploitation. This class is not suitable as a management goal. The management team should move to a higher class to restore the flow pattern of the river.
F (Critically modified)	Modifications have reached a tipping point; the ecosystem has been completely modified with an almost complete loss of natural habitat and biota; in the worst case, the underlying ecosystem functions have been destroyed, and changes are irreversible.	This status is not acceptable from the management perspective. Management interventions are necessary to restore flow patterns and river habitats (if still possible/feasible) to ‘move’ a river to a higher management category.

2.2.3. Flow Duration Curve Analysis

The Flow Duration Curve Analysis (FDCA) method is another popular method used in environmental flow calculations. A typical flow duration curve represents the proportion of flow exceeded for a particular time in the river section. Based on this exceedance curve, the minimum threshold is defined to preserve the ecological integrity of rivers. Generally, indices related to flow duration curves are developed. The maximum abstraction level of water from the river can be subsequently calculated. This method is useful in setting environmental flows downstream of hydropower. The equation used to compute the exceedance probability, which also is referred to as the flow-duration percentile, is given as:

$$P = 100 \times (m / (n + 1)) \quad (8)$$

where P is the exceedance probability, m is the ranking, from highest to lowest, of all daily mean flows for the specified period of record, and n is the total number of daily means flows in the recorded period.

In this study, $Q_{80\%}$, $Q_{85\%}$, and $Q_{90\%}$ are used as low flow indices.

2.2.4. Tennant Method

The Tennant method [45,46] suggested that specific percentages of the average annual flow (AAF) are necessary to maintain a river ecosystem's biological integrity. It assumed that the aquatic organisms' water requirement depends on different life cycles, such as the reproductive stage, global growth stage, etc. These stages have different water requirements. Hence, the method divided the whole year into a spawning period (April–September) and the general growth period (October–March). Table 4 shows the percentage standards of an aquatic organism's water requirement in different life cycle stages.

Table 4. Flow recommendations as per the Tennant method, based on Tennant [45].

Aquatic-Habitat Condition for Small Stream	Recommended Base Flow (% of MAF)	
	General Period (October–March)	Fish Spawning Period (April–September)
Flushing or maximum	200% of the average flow	
Optimum range	60–100	60–100
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair or degrading	10	30
Poor or minimum	10	10
Severe degradation	<10% of average flow to zero flow	

2.2.5. Dynamic Methods

30% of Mean Daily Flow (30%Q-D).

This is based on the concept of minimum daily flow. It releases 30% of mean daily flow, considering a long series of interannual mean daily flow data, allowing for dynamic e-flows releases [47–49].

2.2.6. Mean Annual Flow

At least 10 or 25% of the Mean Annual Flow (MAF) must be released to the downstream depending upon the degree of environmental protection in the river reach. For satisfactory results, at least five years of continuous daily flow data are needed. For more representative results, a long time series of interannual mean daily flow data is required for this method [47].

2.2.7. Indicators of Hydrological Alteration (IHA) and Global Indexes

Richter et al. [50] used 32 “ecologically relevant” hydrological indexes to develop a set of Indicators of Hydrologic Alteration (IHA). The IHA indexes represent five essential parameters of the natural flow regime: magnitude, frequency, duration, timing, and rate of change [51]. The IHA indexes captured most of the variation and information described by 171 indexes, which makes IHA indexes the best choice to represent alteration on rivers [52]. The study used the Richter et al. [53] approach to assess the flow regime and e-flows component (EFC) alteration using relative mean deviation between the natural flow regime (NFR) and e-flows release from the 6 EFMs.

Kuriki et al. [47] proposed a global index for a separate group of IHA indicators to simplify the analysis. Initially, the alteration of each indicator was computed using Equation (9), which is the relative mean difference between natural flow regime (NFR) and altered flow regimes (AFR) divided by *nfr*. Here, *afr* is the regime that will be obtained after releasing the e-flows instead of natural flows. After that, each group’s new global index was computed using Equation (10), each group’s average. The details about indexes are shown in Table 5.

$$HI_{i,j} = \left| \frac{HI_{i,j}(nfr) - HI_{i,j}(afr)}{HI_{i,j}(nfr)} \right| \quad (9)$$

$$I_j = \frac{\sum HI_{i,j}}{N} \quad (10)$$

where $HI_{i,j}$ is the relative mean difference of *i* hydrological indicator of *j* group. I_j : global alteration index of *j* group, $HI_{i,j}(nfr)$: hydrological indicator related to *nfr*, $HI_{i,j}(afr)$: hydrological indicator related to the altered flow regime, and *N*; the total number of IHA indexes for each group. Here, *i* = 1,2–12 depend upon the group and *j* = 1,2,3,4,5. The five indices are classified, as shown in Table 6.

Table 5. List of the Indicators of Hydrologic Alteration (IHA) parameters, their ecological significance, and regime characteristics and global indexes for each IHA group.

Global Index for Each Group	IHA Parameters	Regime Characteristic (Specific Alteration)	Ecological Significance
Mean Monthly Flow Alteration Index (I_{mm})	Group 1: Mean value of each calendar month	Magnitude (increased variation)	Guaranteed favourable habitat conditions and flow regime (quantity, quality, and temperature) for aquatic and terrestrial organisms. Availability of food and cover for fur-bearing mammals.
Magnitude and Duration of Extreme Flow Alteration Index (I_{MDE})	Group 2: Annual minima, 1, 3, 7, 30, 90 day means Annual maxima, 1,3,7,30,90 day means Number of zero-flow days Baseflow index: 7 day minimum flow/mean flow for the year	Magnitude and Duration (prolonged low flows; altered inundation duration; prolonged inundation)	Structuring of aquatic ecosystems by abiotic and biotic factors. The shaping of river channel morphology and physical habitat conditions.
Timing of Extreme Flow Alteration Index (I_{TE})	Group 3: Julian date of each annual 1 day maximum Julian date of each annual 1 day minimum	Timing (oss of seasonal flow peaks)	Disrupt cues for fish: (spawning, egg hatching, migration) [54]. Evolution of the life history and behaviour mechanism of the aquatic organisms [48].

Table 5. Cont.

Global Index for Each Group	IHA Parameters	Regime Characteristic (Specific Alteration)	Ecological Significance
Frequency and Duration Alteration Index (I_{FD})	Group 4: No. of high pulses each year No. of low pulses each year Mean duration of high pulses within each year (days) Mean duration of low pulses within each year (days)	Frequency and Duration (flow stabilization)	Availability of floodplain habitats for aquatic organisms. Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses). Nutrient and organic matter exchanges between river and floodplain.
	Group 5: Means of all positive differences between consecutive daily values Means of all negative differences between consecutive daily values Reversals		
Rate and Frequency Alteration Index (I_{RF})			Wash out and stranding of aquatic species [55]. Failure of seedling establishment [56].

Note: All the ecological significance of the IHA parameters is not listed in the table. A few are listed for more ecological significance; the authors recommend literature related to IHA parameters [51,53,57,58].

Table 6. Range of alteration for global indexes. Where ‘0’ means no alteration while ‘1’ implies the highest alteration.

Range	0.00–0.25	0.25–0.50	0.50–0.75	0.75–1.00
Alteration	Low	Mild	Moderate	High

2.2.8. Environmental Flow Components

The five essential components of flow, namely: low flows, extreme low flows, high flow pulses, small floods, and large floods, have been identified ecologically essential and have been incorporated in IHA software as “environmental flow components” [51]. Each of the flow components has a respective role in the life of an organism. For instance, extreme low flows reduce water connectivity, restricting organisms’ movement; high flow pulses help aquatic mobile organisms move upstream and downstream of rivers. Different species, different geographic conditions, and different rivers (perennial, ephemeral) could be life-threatening, causing the death of organisms or may provide favorable conditions for aquatic organisms for their life stages [51]. The study used the e-flows component (EFC) to assess the alteration using each parameter’s relative mean difference.

2.2.9. Limitations of the Methodology

The hydrological methods are the most simple, straightforward, and data-friendly methods that have been used extensively for the preliminary study of the e-flows allocation [48]. So, when there are several available solutions for the same problem, there is no guarantee of the best solution from both fixed and scientific perspectives. Single flow indices and other hydrological methods (such as Tennant, GEFC, FDC, ADM) have been applied globally, having many advantages. These methods simplify river basin planning work, needless time, and money. They require a low-level of knowledge related to the eco-hydrology of the basins [29,57]. The study’s analysis was limited to hydrological-based e-flows methods, which required only time-series data of mean daily flows [47]. Other sophisticated methods are also available such as habitat simulation and holistic approach, which are more directly involved in ecological concepts. They were not used in the analysis due to a lack of data in the present case study. However, the study can be continued further using those methods if the required data are available.

3. Results

3.1. E-Fows Allocation

Different hydrological methods are used to compute the potential e-flows in the river Table 7 presents the estimated e-flows from different methods. Daily flow data collected over 51 years (between 1964 and 2015) were used to calculate e-flows. The GEFC was used to calculate e-flows for different management classes.

Table 7. E-flow allocation of Kaligandaki River regarding all applied e-flows methods (EFMs).

Method	Classes	(%of MAF)	E-flows (m ³ /s)
GEFC	Class B	47.8	214.46
	Class C	32.8	147.16
	Class D	23.7	106.33
	Class E	18.6	83.45
	Class F	15.7	70.44
Tennant	Oct–Mar	10	44.87
	Apr–Sept	30	134.6
FDC	Q80% FDCA,		49.04
	Q85% FDCA,		45.65
	Q90% FDCA,		43.05
Mean annual flow Dynamic methods	10%MAF		44.97
	30%Q-D		30% of daily flow

Annual Distribution Method												
Month	Jan	Feb	March	April	May	June	July	August	Sep	Oct	Nov	Dec
E-flow (m ³ /s)	60.57	50.05	45.07	49.75	73.54	204.58	646.33	785.59	584.67	274.83	127.61	83.71

This case study only considered Class B classes to Class F, as Class A flows could not be considered as e-flows for any project. The lowest class, 'F', shows 15.7% of MAF, that is, 70.44 m³/s, which indicates that below this amount would characterize the river as a dead environment. An average annual e-flows allocation of 147.16 m³/s (32.8% of MAF) is expected to maintain the essential ecosystem functions. Figures 3 and 4 show the interannual discharge and monthly mean flow of all EFMs.

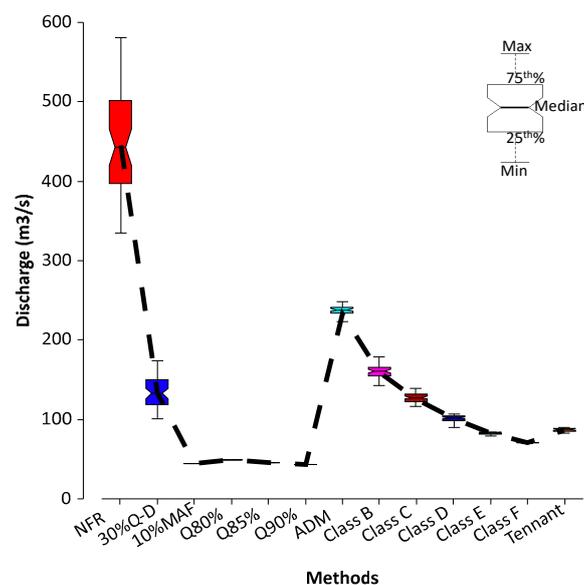


Figure 3. Interannual discharge regarding all applied EFMs. The dashed line connects the mean values of e-flows discharge for each EFMs.

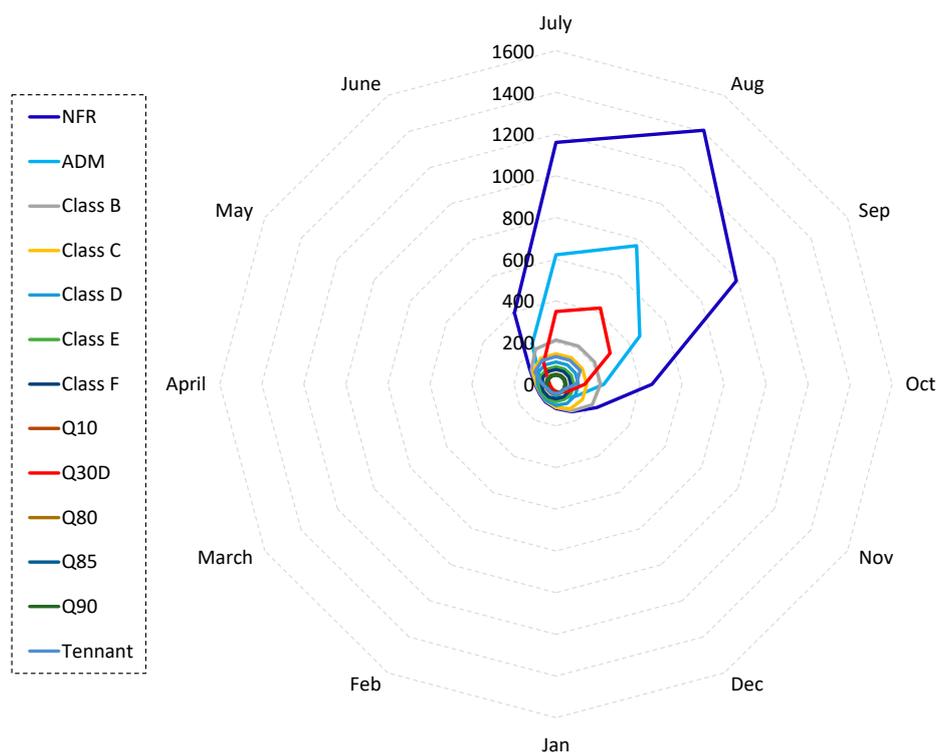


Figure 4. Mean monthly e-flows regarding all EFMs. The year is divided into two parts; the first part refers to high flow seasons (July–December). The second part refers to the low flow seasons (January–June). The reading of the left-vertical axis corresponds to the first part. The reading of the right-vertical axis corresponds to the second part of the year.

The study considers the Tennant method's fair and degrading condition criteria, which allocates 10% of the MAF (equivalent to $44.87 \text{ m}^3/\text{s}$) for the flow from October to March and 30% of the MAF (equivalent to $134.6 \text{ m}^3/\text{s}$) for the flow from April to September. The method is simple and easy to implement, which lets it become more user friendly. It must be noted that 10% of the 6 months' flow is the lowest among all the methods studied. Hence, it may create critical conditions for the river ecosystem during a 10% period.

The mean annual flow method that is 10% MAF allocated $44.97 \text{ m}^3/\text{s}$ to maintain the health of river reach, which is the second-lowest allocation showing its vulnerability of implementation. The dynamic methods of 30%Q-D methods follow the natural hydrograph pattern showing its applicability in the EFs allocation.

The FDC curve could be determined using whole multi-year data, or the FDC curve could be determined for each year separately. Młyński et al. [58] showed significant differences between the Q_p ('p' percentage exceedance discharge) for the multi-year curve and Q_p for mean or median annual curves. The study used multi-year curves to determine the e-flows of the Kaligandaki River. FDC or percentile methods such as Q_{80} , Q_{85} , and Q_{90} was considered for the study. This method allocated e-flows as the mean daily discharge that is equaled or exceeded by 80% (Q_{80}), 85% (Q_{85}), and 90% (Q_{90}). The e-flows suggested by these methods are $Q_{80} = 49.04 \text{ m}^3/\text{s}$, $Q_{85} = 45.65 \text{ m}^3/\text{s}$, and $Q_{90} = 43.05 \text{ m}^3/\text{s}$. The EF estimations from the FDCA methods considered here are less than Class F (equivalent to $70.44 \text{ m}^3/\text{s}$), which critically modified the river ecosystem. Hence, it can be concluded that FDCA methods are not suitable for the EF estimations.

The ADM allocated the lowest e-flows at $45.07 \text{ m}^3/\text{s}$ for March and the highest for August at $785.59 \text{ m}^3/\text{s}$, which is shown in Table 5. The method considered the intra-annual variation of the flow regimes, which can meet the actual need to sustain the ecological function of the river instead of

considering the specific percentages of average annual runoff or specific guarantee rate of frequency curve of natural runoff as e-flows.

3.2. Interannual and Seasonal E-Flows Characterization

Figures 5 and 6 show that the constructed FDC's shape for different EF methods differs from NFR for mean annual flow and seasonal flow (autumn, spring, summer, and winter). The FDC curve of ADM and 30%Q-D methods show a slope, which means this method tries to maintain the rivers' variability, but not by other methods. From the figure, we can see all methods on the FDC curve are below the mean NFR.

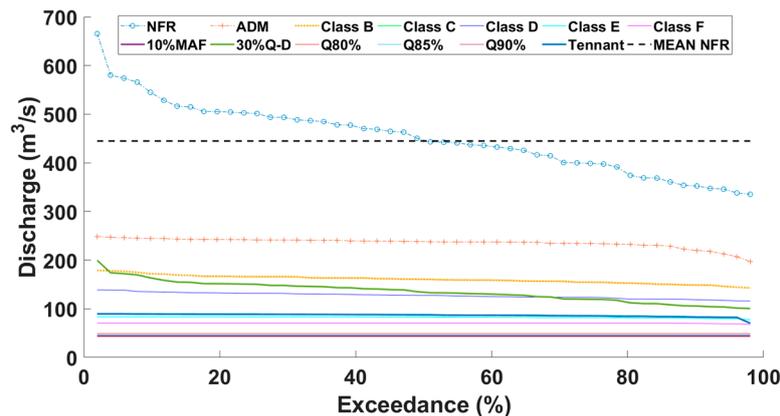


Figure 5. Flow duration curve of interannual mean daily e-flows from 1964 to 2015, regarding of all applied EFMs.

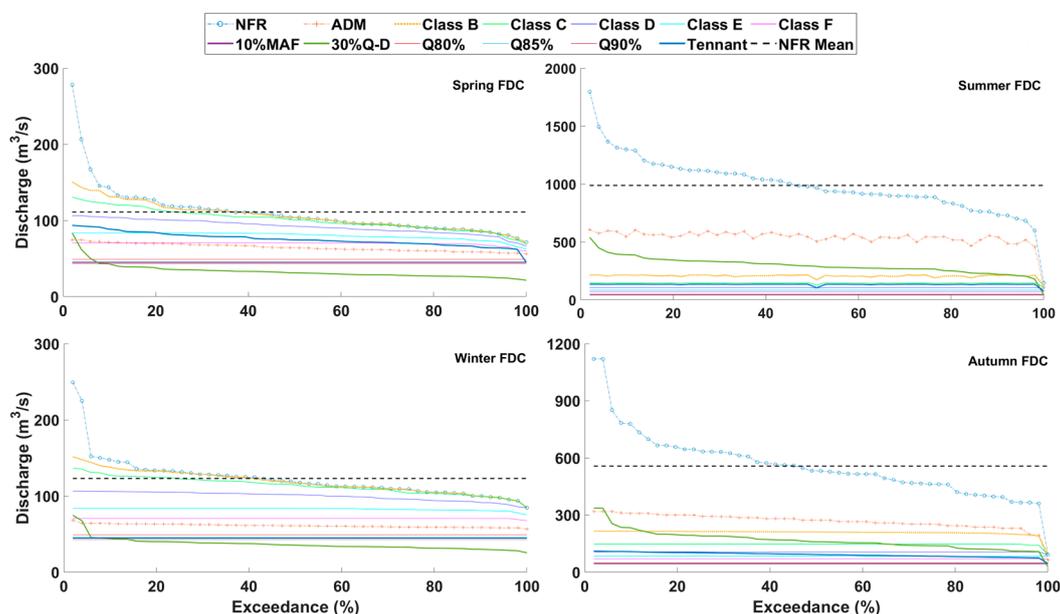


Figure 6. Flow duration curve of seasonal mean daily e-flows regarding of all applied EFMs. Summer (June, July, August), autumn (September, October, November), winter (December, January, February), and spring (March, April, May).

The FDC curve of ADM and 30%Q-D show a similar pattern as NFR but with lower values. Simultaneously, all methods are low flow fixed values methods, represented in a straight line rather than normal FDC curves. The annual mean FDC curves show that all methods value is less than low flows of the NFR, which gives us an idea about the insufficiency of the flow in the river. The seasonal FDC of all methods shows that autumn and summer FDC is the same as the mean annual FDC;

however, FDC of spring and winter shows that Class B and Class C e-flows are higher than mean seasonal flows, which demonstrates suitability for the low flow seasons. In contrast, all other methods are below the mean seasonal flows. The ADM and 30%Q-D methods show a similar pattern as NFR FDC; however, they give very low e-flows during spring and winter seasons. Most of the e-flows methods give a straight line FDC, which means it does not consider the river's flow variability.

The methods which mimic the shape of NFR will be the better methods to sustain the health of the river. In this way, we can choose the different methods for a different season or even different months to take each method's strength and to give one robust method for e-flows calculation in different periods.

3.3. Flow Regime Alteration

3.3.1. IHA Alteration

Figure 7 shows the e-flows regime alteration degree using five indices developed by Kuriqi et al. [47] for all e-flow methods used in the study. The detailed information about the e-flows regime alteration regarding each e-flow method in Appendix A (Table A1). Each method has its strengths and weaknesses, allowing a certain percentage of flow into the rivers. Figure 7 shows the flow alteration due to different EFMs, which may have a high impact on the hydro-ecosystem and related hydro-ecological process.

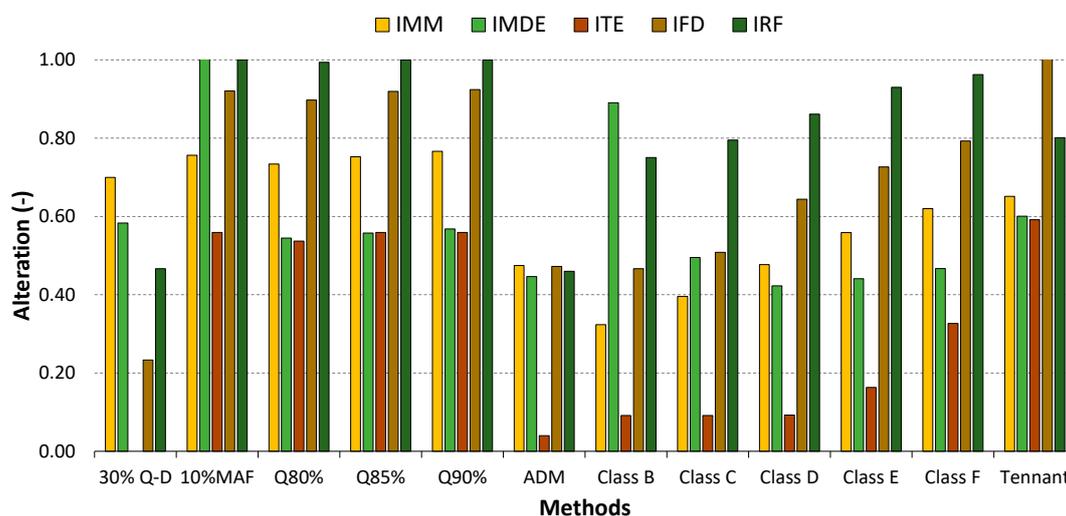


Figure 7. Global indices derived from indicators of hydrological alteration regarding all applied EFMs. Namely, Mean Monthly Flow Alteration Index (I_{MM}), Magnitude and Duration of Extreme Flow Alteration Index (I_{MDE}), Timing of Extreme Flow Alteration Index (I_{TE}), Frequency and Duration Alteration Index (I_{FD}), and Rate and Frequency Alteration Index (I_{RF}). The five indexes are classified into four categories, low (0–0.25), mild (0.25–0.5), moderate (0.5–0.75), and high alteration (0.75–1).

For instance, 10% MAF, Q85%, and Q90% show a high Mean Monthly Flow Alteration Index (I_{MM}). Whereas, 30%Q-D, Q80%, Class E, Class F, and Tennant show moderate I_{MM} . While ADM, Class B, Class C, and Class D show mild I_{MM} . For the second global index, Magnitude and Duration of Extreme Flow Alteration Index (I_{MDE}), only Class B shows great alteration. ADM and Class D show mild alteration while all remaining methods show moderate alteration. Looking at the Timing of Extreme Flow Alteration Index (I_{TE}), 10% MAF, Q80%, Q85%, Q90%, and Tennant show moderate alteration. Only Class B shows mild alteration, but all remaining EFMs methods show low alteration. Frequency and Duration Alteration Index (I_{FD}) shows that environmental management classes Class C, Class D, and Class E show moderate. In contrast, 30%Q-D, ADM, and Class B show low alteration, but other EFMs, for instance, 10%MAF, Q80%, Q85%, Q90%, Class F, and Tennant show high alteration. The Rate and Frequency Alteration Index (I_{RF}), all except ADM and 30%Q-D, show high alteration while ADM and 30% Q-D show low alteration showing these methods effectiveness in e-flows determination.

3.3.2. E-flows Components (EFC)

The study calculated relative changes in the mean of e-flows component (EFC) regarding six EFMs against NFR using the values obtained from IHA software. The results are shown in Table 6. The results show that most of the EFC low flow changes 100% negatively except for 30% Q-D, ADM, and Tennant methods. For 30% Q-D, all EFC Low Flows changes -70% , while in ADM, it varies between -31% during June and 65% during August. The Tennant method varies between -6% during April and -100% for the winter season, extending up to March month. Table 6 shows the relative mean change of the EFC parameters against NFR. Most of the methods, namely 10% MAF, Q80%, Q85%, Q90%, Class B to Class F, show all EFC parameters changes of -100% . While 30%Q-D method shows duration, timing, and frequency of extreme low, high flow, small flood, and enormous flood vary by 0% , and remaining parameters show -70% relative changes against NFR. The ADM method shows a variation of relative mean change within a range between -2% of high flow frequency and $+260\%$ of significant flood frequency.

In comparison, the Tennant method shows a variation between -39% extremely low peak and 1393% extremely low duration. The variability of flow is high when the positive and relative change of C_v is high. In contrast, flow variability is low when C_v 's negative and relative change is of low value.

4. Discussion

The results show that MAF, Tennant (Oct–Mar), and FDC methods allocate e-flows less than the GEFC class F (critically modified) method; hence these methods are not recommended for the e-flows assessment for the present case-study. Further, Class B (Slightly modified) and Class C (moderately modified) allocated a considerable amount of e-flows; however, they gave a fixed value which is a certain percentage of MAF. Nevertheless, river flow is dynamic with interannual variability. Hence, ADM and dynamic method (30%Q-D) are recommended for e-flows allocation. These methods consider the changing characteristics of natural runoff. Hence, to ensure the sustainability of the river health, we must choose the methods that maintain the river's flow dynamics rather than an absolute fixed percentage of MAF of the river.

NFR of many rivers worldwide had been altered by anthropogenic activities such as diversions and impoundment work [5,6,44]. For the rivers with limited data, time, and funding, the hydrological methods are the best method to allocate e-flows. The applied five alteration indexes showed that there is a considerable difference in alteration regarding each EFM. The degree of alteration was varied from EFM to EFM. The EFM, such as ADM and 30%Q-D, appeared to be less altered. This may be due to the consideration of the flow variability of the river [48]. Here, the I_{TE} , I_{FD} , and I_{RF} which have an essential role in sustaining the different ecological processes [54,59], were preserved near NFR, which means they are less altered only for two EFMs, that is, ADM and 30%Q-D. Overall, the results obtained by taking an average of five global indexes showed that the 10% MAF, Q80%, 85%, 90%, and Tennant methods gave high alteration, class D, E, and F showed moderate alterations, indicating their unsuitability in the e-flows allocation. The remaining methods showed mild alterations, indicating the suitability of e-flows allocation. The ADM and 30%Q-D methods showed the lowest and second-lowest alteration among all considered methods with values of 0.380 and 0.406, respectively. This is because the ADM and dynamic methods were the only methods that considered the concept of a dynamic pattern of the river like the NFR.

All six EFMs showed a high alteration of an e-flows component (EFC). Among those methods, except ADM, 30%Q-D, and the Tennant method, all others showed a -100% alteration, confirming the methods' applicability. ADM gave a lower EFC alteration; it showed a monthly low flow alteration between -31% to -65% , resulting from less water in the river than the naturally available water in the riverine ecosystem. The low alteration of monthly flows means it maintains the temperature, flow velocity, and connectivity needed for most of the aquatic habitat than other methods [51]. Extreme low flows, high flow pulses, small floods, and large floods low alterations further give strong supports to the suitability of the method, which is shown in Table 8, because these components play a crucial role in maintaining the health of the rivers [51].

The FDC is a plot of the observed historical river flow data collected with different temporal resolutions daily, weekly, monthly, seasonally, and annually at the gauge station and when that flow is equaled or exceeded [60–62]. The FDC is an informative method that shows the characteristics of flow. The slope of the flow-duration curve is a quantitative measure of the flow regime variability [62]. The NFR FDC generally showed low flows exceeded most of the time while high flows are exceeded infrequently. However, the paper's studied e-flows methods showed low flow exceedance 100% of the time, except for the ADM and 30%Q-D. The FDC curve plotted for annual mean and mean seasonal flows showed a drastic reduction in river flows, especially the high flood. However, the ADM and 30%Q-D methods try to mimic the FDC curve of NFR, which might help sustain the riverine ecosystems' health. Other methods that release fixed minimum flow rather than dynamic release gives a straight line FDC, removing high floods, small floods and it is lower than NFR over the year. The FDC is useful to evaluate the relationship between magnitude and frequency of the river flow; however, it does not maintain temporal sequences of flows and so is unsuccessful in meeting the criteria of the timing or duration of the e-flows [63]. Nevertheless, as recommend by Kuriqi et al. [9,49], to guarantee suitable habitat conditions during low flow periods, AMD and 30%Q-D should be combined with other methods by setting a minimum of e-flows to be released downstream of the water intake. The results of this case study are aligned with the recommendations of the investigations above.

5. Conclusions

In developing countries like Nepal, where ecological information is insufficient and has inadequate baseline data regarding e-flows assessment, the hydrological methods can estimate e-flows requirements for planning and study phases. This study aimed to discuss e-flows calculation methodologies (hydrological) and to discuss the present status of the e-flows in Nepal. We compared six hydrological-based EFMs to allocate e-flows, to evaluate flow alteration, to estimate relative change (%) of the EFC against NFR, and to characterize the interannual and seasonal e-flows of the Kaligandaki River.

The results of the study showed that the global indexes such as Frequency and Duration Alteration Index (I_{FD}) and the Rate and Frequency Alteration Index (I_{RF}) showed a high alteration for all methods, except for the ADM and dynamic method (30%Q-D), which in turn showed a low alteration. The remaining three indexes, namely the Mean Monthly Flow Alteration Index (I_{MM}), the Magnitude and Duration of Extreme Flow Alteration Index (I_{MDE}), and the Timing of Extreme Flow Alteration Index (I_{TE}) showed moderate and mild alteration for all hydrological-based EFMs investigated in this case study. In the overall analysis, it can be seen that the flow alteration of five indexes and the e-flows component (EFC) is lower for ADM and dynamic methods compared to other hydrological methods considered in this study. Furthermore, the FDC of annual mean flows and annual seasonal mean flows showed a dramatic decrease in river flows, especially the high flows in most e-flow methods except for ADM and 30%Q-D methods. This concludes the practicability of the ADM and dynamic methods; it reflects the interannual variability of the river to meet the specific ecological function of the different sections of the river in different periods. Nevertheless, we suggest that the application of those methods should be made under biota requirements at a given river.

The ADM method used in the study was specially designed for large and medium-size perennial rivers, not for temporary or seasonal rivers. The runoff process of these rivers may be intervened more often, which can create a large error in the calculation procedure. Furthermore, many researchers highlighted that the interannual and intra-annual variability of flow in the river must be maintained to sustain the ecological biodiversity. Hence, within hydrological methods, a method that considers the dynamic nature of the flow regime of the river is recommended for the e-flows allocation.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. IHA indicators are showing flow alteration regarding all applied EFMs against NFR.

IHA Parameters	Mean											
	30% Q-D	10% MAF	Q80%	Q85%	Q90%	ADM	Class B	Class C	Class D	Class E	Class F	Tennant
Group #1												
July	0.70	0.96	0.96	0.96	0.96	0.46	0.82	0.87	0.91	0.93	0.94	0.89
August	0.70	0.97	0.97	0.97	0.97	0.46	0.85	0.90	0.92	0.94	0.95	0.91
September	0.70	0.95	0.95	0.95	0.96	0.54	0.79	0.85	0.89	0.92	0.93	0.87
October	0.70	0.90	0.89	0.90	0.91	0.50	0.54	0.68	0.77	0.82	0.85	0.79
November	0.70	0.80	0.78	0.80	0.81	0.50	0.12	0.35	0.53	0.63	0.69	0.79
December	0.70	0.70	0.68	0.70	0.72	0.50	0.03	0.10	0.30	0.45	0.54	0.70
January	0.70	0.62	0.58	0.61	0.63	0.50	0.05	0.06	0.14	0.29	0.40	0.62
February	0.70	0.55	0.51	0.54	0.57	0.52	0.05	0.06	0.08	0.18	0.29	0.55
March	0.70	0.50	0.45	0.49	0.52	0.49	0.04	0.05	0.06	0.14	0.23	0.50
April	0.70	0.54	0.50	0.54	0.56	0.46	0.04	0.06	0.10	0.20	0.30	0.35
May	0.70	0.69	0.66	0.68	0.70	0.34	0.05	0.14	0.29	0.42	0.51	0.19
June	0.70	0.89	0.88	0.88	0.89	0.43	0.51	0.64	0.73	0.79	0.82	0.67
Group #2												
1-day minimum	0.70	1.10	0.09	0.07	0.06	0.02	0.69	0.00	0.00	0.02	0.06	0.32
3-day minimum	0.70	0.39	0.34	0.38	0.42	0.42	1.00	1.00	0.00	0.03	0.10	0.39
7-day minimum	0.70	0.41	0.35	0.40	0.43	0.42	1.00	0.00	0.00	0.04	0.11	0.41
30-day minimum	0.70	0.46	0.41	0.45	0.48	0.46	1.00	0.02	0.03	0.09	0.18	0.46
90-day minimum	0.70	0.51	0.47	0.50	0.53	0.47	1.00	0.03	0.05	0.14	0.24	0.51
1-day maximum	0.70	0.99	0.99	0.99	0.99	0.64	1.00	0.96	0.97	0.98	0.98	0.97
3-day maximum	0.70	0.99	0.98	0.98	0.99	0.59	0.93	0.95	0.96	0.97	0.98	0.96
7-day maximum	0.70	0.98	0.98	0.98	0.98	0.53	0.91	0.94	0.95	0.96	0.97	0.94
30-day maximum	0.70	0.97	0.97	0.97	0.97	0.51	0.87	0.91	0.94	0.95	0.96	0.92
90-day maximum	0.70	0.96	0.96	0.96	0.96	0.49	0.83	0.88	0.91	0.93	0.94	0.89
Number of zero days	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Base flow index	0	4.580357	0.0008	0.000801	0	0.8071	1.455677	0.255647	0.253194	0.184867	0.080163	0.452621
Group #3												
Date of minimum	0.000	0.94	0.90	0.94	0.94	0.05	0.00	0.000	0.000	0.148	0.475	1.000
Date of maximum	0.00	0.18	0.18	0.18	0.18	0.03	0.18	0.18	0.185	0.178	0.178	0.183

Table A1. Cont.

IHA Parameters	Mean											
	30% Q-D	10% MAF	Q80%	Q85%	Q90%	ADM	Class B	Class C	Class D	Class E	Class F	Tennant
Group #4												
Low pulse count	0	1	0.988495	1	1	0.709692	0	0.067454	0.272659	0.580616	0.736016	1
Low pulse duration	0.00	1.00	0.91	1.00	1.00	0.41	0.00	0.09	0.56	0.61	0.75	1.00
High pulse count	0.00	1.00	1.00	1.00	1.00	0.29	1.00	1.00	1.00	1.00	1.00	0.44
High pulse duration	0.00	1.00	1.00	1.00	1.00	0.46	1.00	1.00	1.00	1.00	1.00	4.56
Low Pulse Threshold	0.70	0.57	0.53	0.56	0.59	0.45	0.01	0.05	0.14	0.25	0.34	1.00
High Pulse Threshold	0.70	0.96	0.95	0.96	0.96	0.52	0.79	0.85	0.89	0.92	0.93	0.88
Group #5												
Rise rate	0.70	1.00	0.99	1.00	1.00	0.67	0.91	0.93	0.96	0.97	0.98	0.86
Fall rate	0.70	1.00	0.99	1.00	1.00	0.63	0.90	0.92	0.94	0.95	0.97	0.68
Number of reversals	0.00	1.00	1.00	1.00	1.00	0.08	0.44	0.53	0.69	0.86	0.94	0.87

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