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Applicability of Environmental Flow Techniques in Himalayan Hydropower Considering Hydrologic and Energy Perspective: A CASE study of Kali Gandaki River Basin

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ABSTRACT. Environmental flow (e-flow) management is a critical issue in Himalayan river basins, particularly in the context of rapid hydropower development. The prevailing practice of maintaining a uniform, year-round static e-flow release (typically 10% of the minimum monthly flow) is often inadequate to sustain riverine ecological health while balancing hydropower generation objectives, especially during the dry season. This study evaluates the applicability of seven e-flow assessment methodologies by integrating hydrological reliability and hydropower generation impacts in Kali Gandaki river basin. Different e-flow methods are assessed in terms of hydrologic failure and the resulting alterations in energy production. Results showed that method-wise variability in e-flow demand does not differentiate between rain-fed and snow-fed hydrological characteristics. Annual Distribution Method (ADM), Department of Electricity Development (DoED) guideline, and Modified Minimum Flow Method (MMFM) exhibit negligible hydrological failure rates. Methods such as ADM and MMFM demonstrate relatively lower impacts on annual and dry-season energy generation. In contrast, more stricter approaches such as the Variable Monthly Flow (VMF), Tessmann, and Tennant methods show lower hydrological reliability and significantly higher impacts on energy generation. The findings highlight the need for a comprehensive evaluation of dynamic e-flow strategies to support sustainable planning and operation of hydropower projects in the Himalayan region.

Keywords: DoED, Environmental Flow (E-flow), Hydropower, Hydropower Generation; Run-of-River (RoR)

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1. INTRODUCTION

Characterized by negligible greenhouse gas emissions and other harmful pollutants, hydropower energy is globally recognized as a leading cleaning energy source and plays a vital role in atmospheric decarbonization to mitigate global temperature ([3]; [9]). Characterized by steep topography, snow-fed rivers and strong monsoonal rainfall, Nepal is very rich in freshwater resources (about 2.27% of the world's freshwater resources) [4]. There is a huge potential in hydropower development which serves as a cornerstone for the nation's economic growth[15].

Hydropower plants generate electricity by diverting water from rivers to turbines via diversion structures. This results in reduced flow within the diverted river stretch which causes the disturbance in riverine ecosystem such as impact on aquatic life, sediment transport process and negative impact on the communities dependent on downstream water ([5]; [18]). To mitigate the ecological impacts, the application of environmental flow (e-flow) has gained increasing importance in global hydropower development. According to Brisbane Declaration and Global Action Agenda (2018), e-flow is defined as "the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems [7, 8].

Although hydropower development in Nepal span over a century ago, e-flow requirements were significantly unaddressed until the introduction of the Water Resources Act (1992) [15]. Later, the Hydropower Development Policy (2001), explicitly specifies the required quantity of minimum flow to be maintained ([15]; [17]). The policy states that "Provision shall be made to release such quantum of water which is higher of either at least ten percent of the minimum monthly average discharge of the river/stream or the minimum required quantum as identified in the environmental impact assessment study report" ([1]; [17]). Furthermore, The Department of Electricity Development (DoED) guidelines states that "A compensation flow (10% of lowest monthly flow or amount of downstream release recommended by IEE/EIA study) should be released downstream, which should be deducted from the available dry season flows for the computation of the energy estimates." ([6]). While, the DoED guidelines frameworks allow for seasonal variability via IEE/EIA which are designed to protect riverine ecosystems, the operational practice neglect the seasonal e-flow requirement recommended by the IEE/EIA report and defaults to a static minimum flow i.e., 10% of the lowest monthly flow. Hence, this provision provides a constant minimum flow which does not fully account for the natural flow regimes, overlooking the river's seasonal variability and the requirements for maintaining a healthy riverine ecosystem ([15]). Furthermore, diminished instream flows significantly compromise the livelihoods of downstream communities in river due to shortage of water for fisheries, irrigation and other daily uses ([20]).

The objective of e-flow is to align water management practices with ecological needs ([14]). It acts as a safeguard for riverine ecosystem by supporting aquatic life and fish migration and spawning cycles remain uninterrupted [7]. Furthermore, e-flow provides socio-economic advantages to downstream communities, through the enhancement of fisheries and tourism[19]. Augmenting e-flow allocations improve the ecological health of the river but this reduces the quantity of water diverted to the turbine, consequently reducing hydropower generation lowering plant factor and annual energy yield, especially during dry season for RoR projects.

Globally, several hydrological e-flow methodologies have been developed to better represent seasonal and ecological flow needs. However, most of these methods were derived empirically from temperate river systems, possessing different climatic and hydrologic characteristics distinct from those of Nepal. These different e-flow methodologies yield different e-flow prescriptions based on their respective computational robustness. One of the major gaps in Nepalese hydropower development is the lack of comprehensive research on the suitability, applicability and the use of various e-flow methods (originally derived from rivers with different climatic and hydrological characteristics) under Himalayan hydrologic condition ([17]). This study aims to study the applicability of these methods within the snow-fed, glacier-influenced, and monsoon-dominated watersheds of Nepal. With the quantification of both their ecological reliability (hydrological failure rate percentage) and resultant impacts on energy generation relative to current DoED standards, clear

evidence can be gathered showing why some of these methods need rigorous calibration before being implemented in Nepal's river basins.
Previously, Rijal & Alfredsen (2015) [15] conducted a study in Upper Trishuli-I Hydroelectric project using Modified Tennant Method and concluded that the requirement imposed by DoED to release 10% of the minimum mean monthly discharge does not adequately consider project specific conditions or field based hydraulic assessments. Furthermore, a study conducted in the Kali Gandaki River Basin by [17] which evaluated the applicability of six different hydrological rating e-flow methodologies to assess flow alteration. This study advocated a shift from static minimum flow prescriptions toward more dynamic, variability-based hydrological methods for e-flow assessment in Himalayan river systems [17]. Singh (2025) [16] conducted a study to design and implement an optimization model for a multi-reservoir system within the Bheri river basin. By evaluating e-flow management scenario alongside regulated streamflow from these optimized reservoir operations, this study found that the e-flow methods are effective and can be applicable after reservoir operation (Singh, 2025).

2. MATERIALS AND METHODS

2.1. **Study Area.** Kali Gandaki river basin is one of the important sub-basins of the Gandaki basin, having a catchment area of approximately 11,830 km^2 and elevation varying from 188 m to 8143 m [11]. This is a critical basin, possessing major operating and planned RoR/PRoR hydropower projects. Figure 1 shows the area map of the Kali Gandaki river basin.

2.2. **Hydrological Data.** The main dataset consists of monthly mean flow time series for hydrological gauging stations across Nepal. Hydrological information is obtained from the Department of Hydrology and Meteorology (DHM). A good quality time series were checked for continuity and outliers, ensuring a minimum period of 30 years. In this study, two hydrological stations are taken as a proxy for hydropower projects such as stations 406.5 (Modi Khola, Jharpe Bagar) and 419.1 (Kali Gandaki, Angsing) as these stations are at close proximity to major hydropower projects such as Kali Gandaki "A" hydropower project and Modi Khola hydroelectric power plant. The features of hydrological stations are shown in the Error: Reference source not found.

Table 1. Studied Hydrological Stations

St. ID	River	Location	Latitude	Longitude	Elevation	Start Year
406.5	Modikhola	Nayapul	28.2542	83.7242	701	1976
419.1	Kali Gandaki	Ansing	27.8847	83.7950	351	1996

2.3. **Methods.** This study used multi-model framework integrating hydrologic observation, e-flow modeling, energy generation model. The study follows a multi-stage computational workflow to assess the impact of various E-flow methods on both river health and hydropower generation as shown in Figure 2.
Initially, a monthly flow series was established using hydrological data from two stations such as 406.5 and 419.1 within the Kali Gandaki station. To determine monthly e-flow demand, seven hydrological e-flow methods are used- namely Tennant, Tessman, ADM, Q90_Q50, VMF, MMFM, and DoED.
Then, a failure assessment is done to assess whether the natural flow can sustain the monthly demand calculated under each method across the historical years. Finally, the study quantified the energy difference in RoR projects using six method is calculated with respect to DoED method turbine release. The methods are briefly explained in the following section.

2.3.1. *Calculation of E-flow Demand.* Selection of a suitable EFM depends on several variables, such as the accessibility of hydrological data, regional characteristics, ecological needs, water management objectives, and the existing e-flows standards. This study used multiple hydrological methodologies to calculate e-flows at hydrological stations. Here, hydrological gauging stations

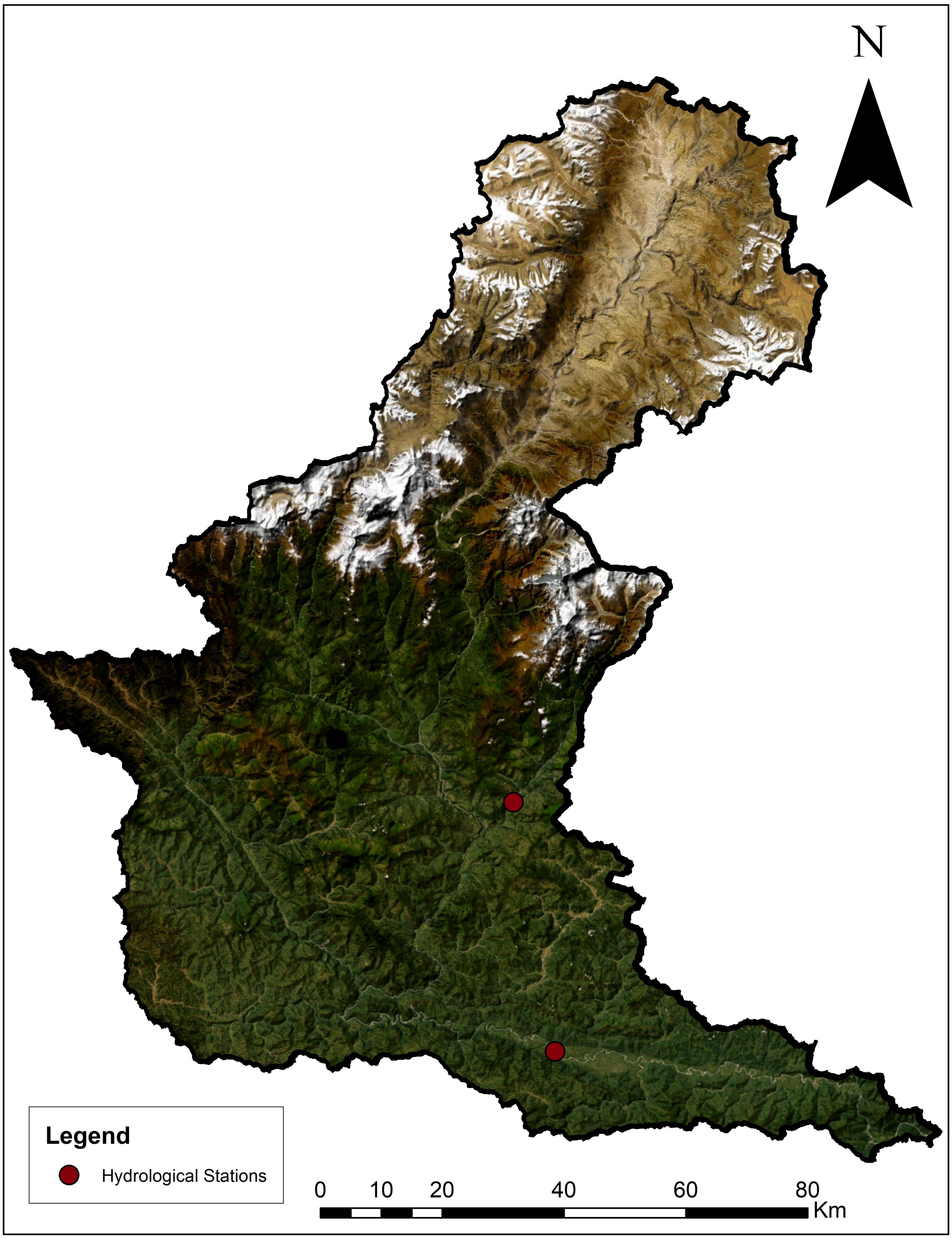

FIGURE 1. Study Area Map of Kali Gandaki River Basin

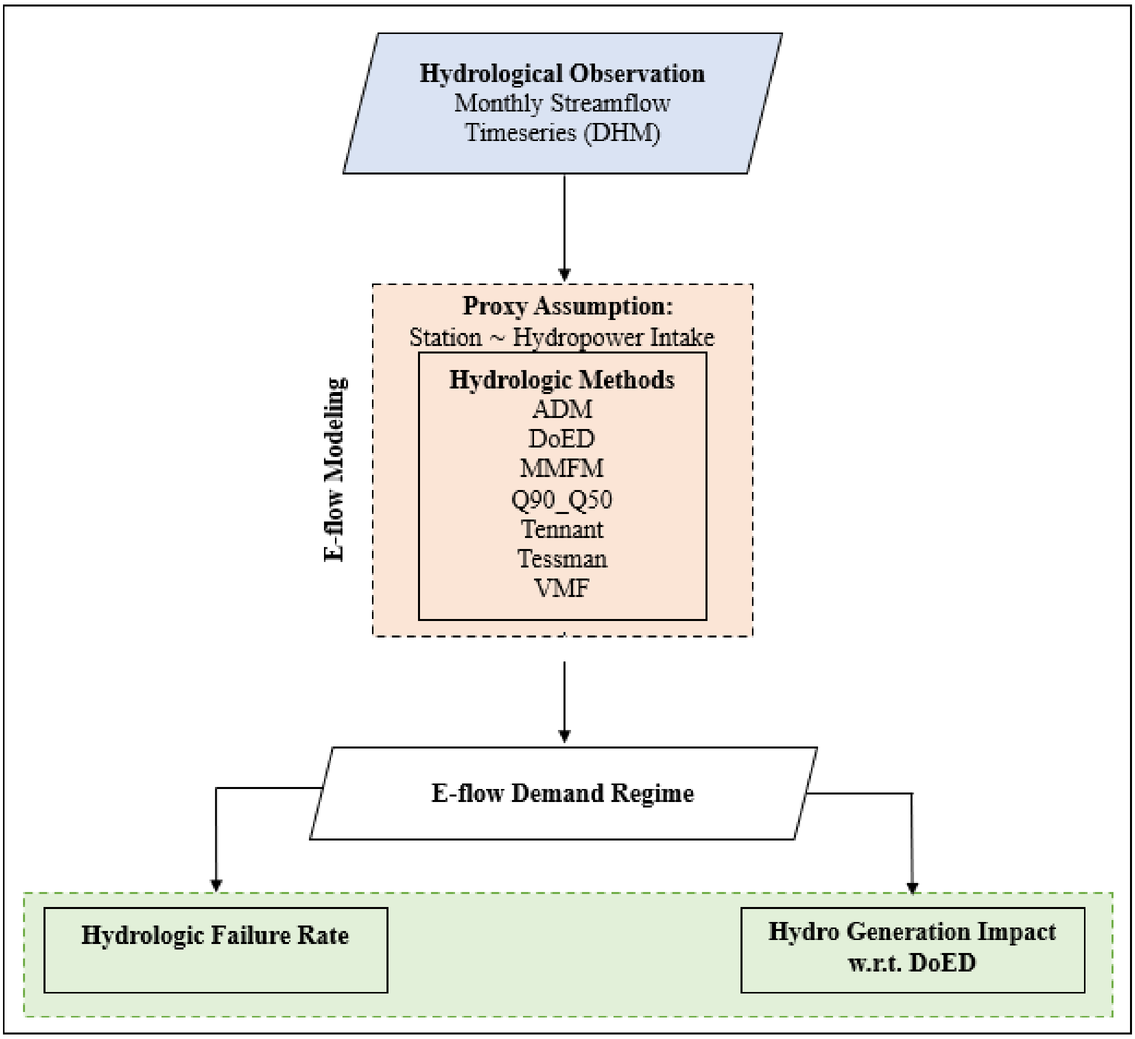

FIGURE 2. Overall Methodological Framework of the study

are utilized as proxies for hydropower intake locations. The following Equations (1)–(7) define the e-flow (EF_t) calculations under the various methods used in this study, where Q_t is the monthly inflow at time t (m^3/s), and $Q_{\min,t}$ is the historical minimum flow for month t (m^3/s).
DOED Guideline: This rule follows DOED guideline which allocates maximum of 10% of the minimum recorded flow e-flow requirement (DoED, 2018).

$$EF_t = 0.1 \times \min(Q_t), \quad t = 1, 2, \ldots, 12 \tag{1}$$

Annual Distribution Method (ADM):. This method determines e-flow as a percentage of the monthly inflow, indexed against the ratio of minimum monthly inflow to MAF. This method operates under the assumption that maintaining average monthly river preserves fundamental ecological needs, maintains aquatic life and avoid significant degradation to the river ecosystem [17].

$$EF_t = \left(\frac{\min(Q_t)}{MAF}\right) \times Q_t, \quad t = 1, 2, \ldots, 12 \tag{2}$$

Tennant Method: For this study, fair conditions for fish survival were adopted as the analytical basis, allocating corresponding e-flow requirements for both the wet and dry seasons [12].

$$EF_t = \begin{cases} 0.3 \times MAF & \text{if } t \in \{OCT - MAR\} \\ 0.1 \times MAF & \text{if } t \in \{APR - SEP\} \end{cases} \tag{3}$$

Tessman Method: Tessman method is a modification of the Tennant method that incorporates monthly flow variations for better reflection of natural seasonal variability of river.

$$EF_t = \begin{cases} Q_t & \text{if } Q_t \leq 0.4 \times MAF \\ 0.4 \times MAF & \text{if } Q_t > 0.4 \times MAF \\ 0.4 \times Q_t & \text{otherwise,} \\ & t = 1, 2, \ldots, 12 \end{cases} \tag{4}$$

Monthly Minimum Flow Method (MMFM):. Under this approach, e-flow is defined as 10% of the historical minimum discharge for each month. To remain aligned with DoED guidelines, a modification is applied: if $Q_{\mathrm{min,t}}$ falls below the minimum monthly flow, EF_t is set equal to the lower value.

$$EF_t = \begin{cases} 0.1 \times Q_{min,t} & \text{if } Q_{min,t} \geq \min(Q_t) \\ 0.1 \times \min(Q_t) & \text{otherwise} \end{cases} \tag{5}$$

Q_{90}-Q_{50} Method: This method is a non- parametric approach allocating the 50^{th} percentile flow to environmental factors during wet seasons and 90th percentile flow during dry seasons [12, 13]

$$EF_t = \begin{cases} Q_{90} & \text{for dry months} \\ Q_{50} & \text{for wet months} \end{cases} \tag{6}$$

Variable Monthly Flow Method (VMF):. This approach adjusts e-flow requirements to monthly flow conditions, thereby accounting for seasonal variability. It incorporates both dry and wet season characteristics to address dynamic flow needs [13].

$$EF_t = \begin{cases} 0.6 \times Q_t & \text{if } Q_t \leq 0.4 \times MAF \\ 0.3 \times Q_t & \text{if } Q_t > 0.8 \times MAF \\ 0.45 \times MAF & \text{otherwise,} \\ & t = 1, 2, \ldots, 12 \end{cases} \tag{7}$$

2.3.2. *Assessment of Hydrologic Failure Rate.* The ecological suitability of a method is assessed by its hydrologic failure rate (f), which can be defined as the percentage of months where the natural flow is insufficient to meet the prescribed e-flow demand. A failure occurs when the available river flow cannot meet the demand. Failure rate is given by:

$$f = \frac{\text{Months where } Q_{available} < Q_{eflow}}{\text{Total Months}} \times 100\% \tag{8}$$

Methods having low failure rates (f <10%) indicate they are ecologically reliable. i.e., The natural flow is able to meet the prescribed e-flow 90% of the time. Meanwhile, when methods exhibit higher failure rate (f >30%), they possess high ecological risk. This implies that the e-flow demand of the method is unrealistic for the river's hydrology.

2.3.3. *Hydropower Impact Assessment.* Increasing the e-flow demand means more water is allocated in the river for the protection of riverine ecosystem. However, this reduces the flow in the turbines which results in the loss of hydro energy generation. The impact on energy generation is calculated by comparing the energy produced under six e-flow method against the current DoED baseline. For RoR projects, the turbine flow (Q_{turb}) is constrained by the design discharge (Q_{d} taken as Q40) and the required e-flow (Q_{ef}). Q_{turb} is calculated by the assumption illustrated in equation (9).

$$Q_{turb} = \min(Q_{river} - Q_{ef}, Q_{40}) \tag{9}$$

For RoR operation, hydro energy is a function of net head (H) and turbine discharge (Q_{turb}), where Q_{turb} is the water left after subtracting the e-flow requirement. Following Equation (10), the energy generation formula has been used:

$$E = \eta \times \rho \times g \times H \times Q_{\text{turb}} \times t \tag{10}$$

where η is the turbine efficiency, ρ is the water density, g is the acceleration due to gravity, H is the net head, and t is the operational time.
Hydropower generation loss (L) is given by Equation (11):

$$Loss = \left[\frac{Energy_{DoED} - Energy_{Method}}{Energy_{DoED}}\right] \times 100\% \tag{11}$$

3. RESULT AND DISCUSSION

This study is based on the two hydrological stations which are taken as a proxy to hydropower projects within the Kali Gandaki river basin. The results including e-flow demand variability, reliability in Himalayan hydrologic regime and energy generation impact are presented below:

3.1. E-flow Demand Variability.

Figure 3 and Figure 4 show the e-flow monthly e-flow demand at 419.1 (Kali Gandaki, Angsing) and 406.5 (Modi Khola, Jharpe Bagar) respectively. As shown in the figures, method such as DoED and MMFM yield the lowest e-flow demand and maintain nearly constant flow values year-round which fails to reflect river's natural hydrological variability. In contrast, VMF method demands highest e-flow values. Tessman method and Q90_Q50 method also provide significant e-flow values which means this method reflects seasonal variation. While these methods are more suitable for sustaining river's health, they significantly reduce the water available for hydropower generation. Other methodologies, such as ADM and Tennant methods, only partially follow the river's natural variability. This suggests that these methods provide a baseline level of ecological protection (showing seasonal variability) while also allowing for water diversion for hydropower generation.

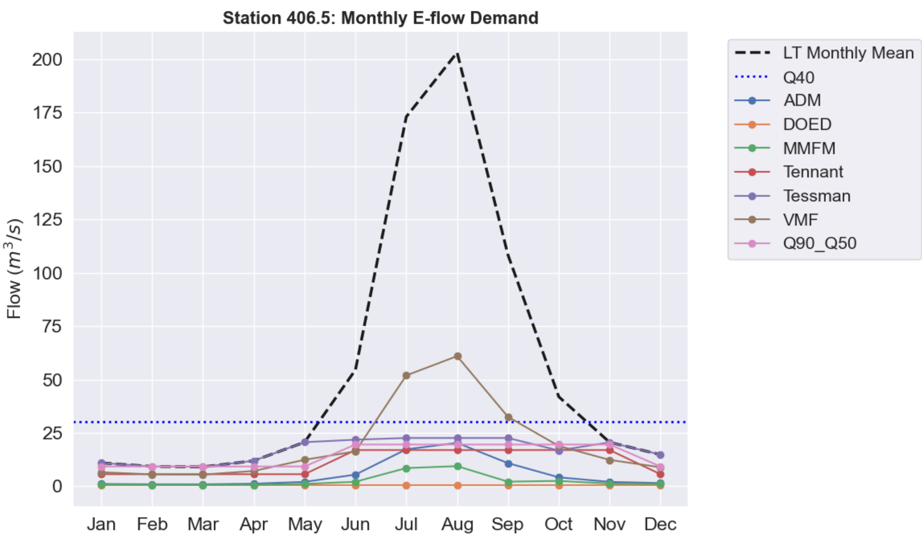

FIGURE 3. Monthly e-flow demand in the Kali Gandaki basin at 406.5 (Modi Khola, Jharpe Bagar).

3.2. **Reliability in Himalayan Hydrologic Regime.** This study tested the suitability of six hydrologic e-flow methods at two hydrologic stations within Kali Gandaki basin. Error: Reference source not found shows the hydrological failure rate percentage during the dry season. From Figure 5, several e-flow methodologies such as DoED, ADM, MMFM, Tennant and VMF methods show minimal failure rate which signifies these methods are hydrologically suitable for the calculation of e-flow values in Kali Gandaki basin. Meanwhile, other stricter e-flow methods such as Tessman and Q_{90}-Q_{50} methods exhibit hydrological failure rate of more than 50% and 20% for both stations respectively. These results indicate that Tessman and Q_{90}-Q_{50} methods may not be applicable in the basin.

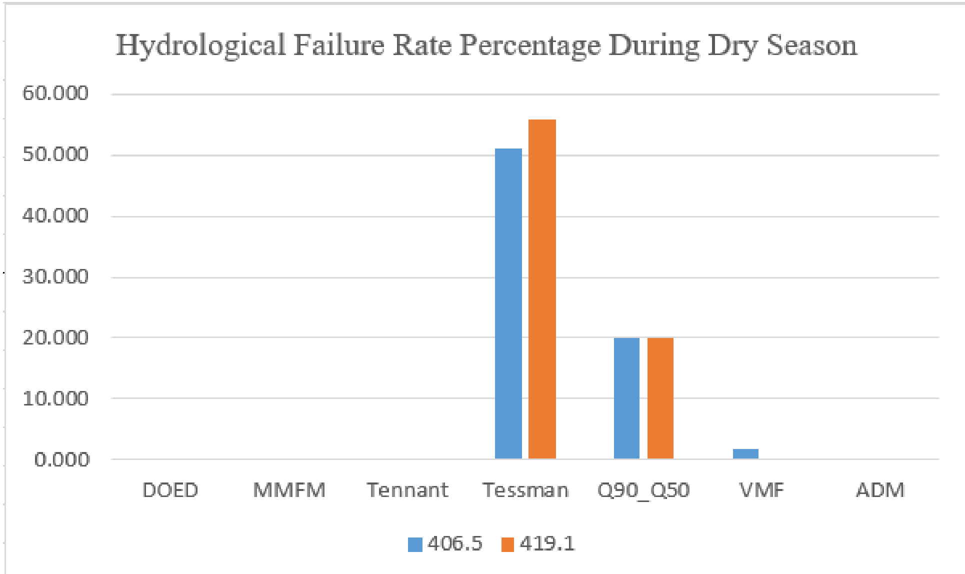

FIGURE 4. Hydrological Failure Rate Percentage During the Dry Season.

3.3. **Energy Generation Impact.** This study determined the energy generation impact under six hydrologic e-flow methods at two hydrologic stations within the Kali Gandaki basin. Figure 6 illustrates hydropower generation loss under various methods w.r.t. DoED. MMFM exhibit minimal energy loss as demonstrated in . Furthermore, ADM results in less than 20% energy loss for both stations. Meanwhile, other stricter e-flow methods yield higher energy loss more than 40% in case of Tennant method and up to 100% in the case of Tessman and Q_{90}-Q_{50} methods.

3.4. **Trade-off Analysis Under Various E-flow Strategy.** Table 2: Trade-off Analysis of Ecological Integrity vs Impact on Energy Generation
Table 2 shows the trade-off analysis between ecological integrity and impact on energy generation under different e-flow strategy during dry season. From this table, ecological protection level of standard baseline (10%) is quite poor. Meanwhile, the report from IEE/EIA of projects shows moderate ecological protection level but often aren't monitored. Other stricter methods such as Tessman and Q_{90}-Q_{50} methods have higher hydrological failure rate and higher impact on dry season energy generation. Thus, these methods are not applicable in Himalayan rivers. Meanwhile, ADM show minimal hydrological failure rate and have low impact on dry season energy generation w.r.t. DoED. Furthermore, ADM follows the seasonal variability of the river and thus this method provides good ecological protection level.

4. CONCLUSIONS

This study employs an integrated framework to assess the applicability of various e-flow methodologies in Himalayan river basin based on the calculation of their hydrologic failure rate and their

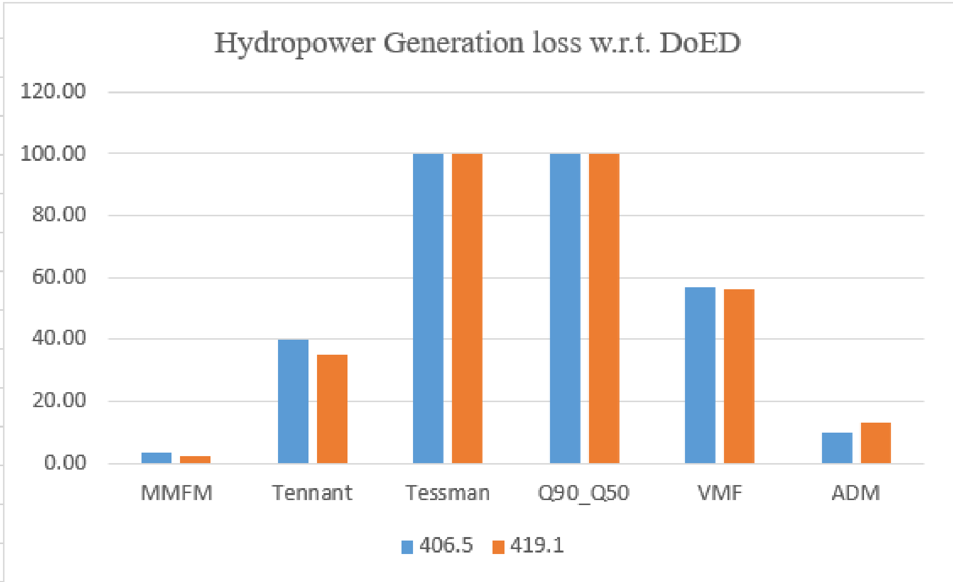

FIGURE 5. Hydropower generation loss under various methods with respect to DoED.

TABLE 2. Trade-off Analysis of Ecological Integrity vs. Impact on Energy Generation

E-flow Strategy	**Hydrological Failure Rate (Dry Season)**	**Impact on Dry Season Energy Generation**	**Ecological Protection Level**
DoED Standard Baseline (10%)	Minimal	Minimal	Poor (static; risks ecological degradation)
IEE/EIA Project Target	Low (< 10%)	Variable	Moderate (site-specific but often unmonitored)
ADM	Minimal	Low	Good (follows seasonal variability of the river)
Tessman / Q90–Q50 Methods	High (> 50% / > 20%)	High (up to 100%)	High, but not applicable in Himalayan rivers due to the higher failure rate and greater impact on energy generation)

impact on hydro generation. From this study, we can conclude that conservative methods like MMFM do not follow the seasonal variability of the river and exhibit similar result to the DoED. Conversely, other stricter e-flow methods impose higher e-flow requirements while showing seasonal variability, but they suffer from a higher failure rate (more than 50%) and higher energy generation loss (up to 100%). Consequently, these methods are not applicable. This signifies that increasing e-flow requirements does not necessarily guarantee ecological preservation; rather, excessive allocations can lead to higher ecological failure rate as shown by Tessman and Q_{90}-Q_{50} methods. From all the results, ADM is found to be the most suitable and reliable e-flow method among seven e-flow methods tested for Himalayan rivers, as it mimics the seasonal variability of the river providing ecological safeguards, is hydrologically supported (with a negligible failure rate), and has a lower impact on energy generation (less than 20%).

5. RECOMMENDATIONS

Based on the findings and conclusions, the following recommendations are made for further study and implementation:

- To enhance the health of riverine ecosystem without compromising energy production, this study recommends that "one-size-fits-all" strict policies should not be applied in favor of prioritizing more dynamic e-flow methodologies.
- As ADM follows the seasonal variability of the river without significantly compromising hydropower, this method is recommended to replace the current DoED baseline for e-flow determination for hydropower projects.
- E-flow method requires a site-specific technical review, which makes it more reliable. Hence, policy makers should allocate their budget towards the technical reviews required for dynamic method instead of other unfeasible e-flow methodologies.
- In addition to hydrologic e-flow assessments, other methods such as hydraulic, habitat simulation, and holistic methods should be considered.
- Future streamflow projection under climate change should be developed by integrating hydrological model.

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