Environment and Ecology Research 11(6): 1010-1022, 2023 http://www.hrpub.org
DOI: 10.13189/eer.2023.110612

Synergizing Ecology and Economy: Developing a Novel Ecology-Economy Index for Sustainability Analysis of the Bharalu River, India

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Received August 7, 2023; Revised November 27, 2023; Accepted December 21, 2023

Cite This Paper in the Following Citation Styles

(a): *[1] Unmilan Kalita, Amlan Kumar Dey, Padma Sharma Goswami, Arup Kumar Hazarika, Suraj Chetri, Binita Basnet Baruah, Jyotismitra Das , "Synergizing Ecology and Economy: Developing a Novel Ecology-Economy Index for Sustainability Analysis of the Bharalu River, India," Environment and Ecology Research, Vol. 11, No. 6, pp. 1010 - 1022, 2023. DOI: 10.13189/eer.2023.110612.*

(b): *Unmilan Kalita, Amlan Kumar Dey, Padma Sharma Goswami, Arup Kumar Hazarika, Suraj Chetri, Binita Basnet Baruah, Jyotismitra Das (2023). Synergizing Ecology and Economy: Developing a Novel Ecology-Economy Index for Sustainability Analysis of the Bharalu River, India. Environment and Ecology Research, 11(6), 1010 - 1022. DOI: 10.13189/eer.2023.110612.*

Abstract Rivers play a critical role in supporting both ecosystems and human activities, underscoring the significance of their environmental conservation. Unfortunately, the rapid rise of industrialization and urbanization has led to severe pollution and ecological degradation in many rivers worldwide. In this study, we focus on the degrading ecological condition of the Bharalu River - a crucial tributary of the Brahmaputra River in India and explore the intricate connection between economic activities and the river's ecological quality in the river's watershed. To achieve this, a novel Ecology-Economy index (EEI) is introduced, providing a comprehensive evaluation of how economic development impacts the river's ecological condition. Findings reveal a very high EEI value of 0.706 revealing a high interaction between the ecology-economy, demonstrating a troubling ecological impact resultant from economic activities, leading to significant environmental degradation. As such, in order to restore and protect the health of the Bharalu River, efforts should prioritize attaining a lower Ecology-Economy index ratio. This would signify a better balance between economic growth and ecological sustainability, ultimately mitigating the adverse effects on the river's ecological status.

Keywords Ecology, Economics, Brahmaputra River, Bharalu River, Ecological Restoration

1. Introduction

River systems, with their intricate network of channels, form the lifeblood of our ecosystems, facilitating the flow of water, sediments, and diverse substances that drive a myriad of interconnected natural processes. These processes have given rise to the earth's freshwater biodiversity, comprising abundant flora and fauna within floodplains and lakes [1]. Rivers create the physical environment where these species thrive, engaging in life activities like reproduction, feeding, and movement. Many organisms spend their entire lives within rivers, while others rely on them for sustenance or as a source of water [2]. Rivers have proven to be indispensable resources, providing an uninterrupted supply of freshwater for drinking and irrigation, fertile floodplains supporting thriving agriculture, valuable nutrition, and serving as major transportation routes. Throughout history, rivers have been integral to economic systems, supporting agriculture, trade, transportation, and cultural interchange [3]. As we confront the challenges of the 21st century, these waterways remain essential pillars of global economies.

The Indian subcontinent is known for its elaborate river systems with their vast networks draining the entirety of its region. However, of late, India is suffering from the plague of pollution which has severely affected its major river systems, such as the Ganga, Yamuna, and the Brahmaputra. The Ganga and Yamuna, considered as one of the world's most polluted rivers, are suffering from pollution resulting from heavy industrial discharge, untreated sewage, and agricultural runoff [4]. The Brahmaputra River, a significant transboundary river originating in the Tibetan Plateau (known as the Yarlung Tsangpo), passes through the Indian states of Arunachal Pradesh and Assam before reaching Bangladesh. During its course, the river faces similar challenges, with high levels of pollution from industrial effluents and untreated sewage [5]. The river's water quality deteriorates significantly in the state of Assam, India. This degradation can be attributed to the inadequate waste management infrastructure in the state as well as the heavy pollution of its tributary, the Bharalu river.

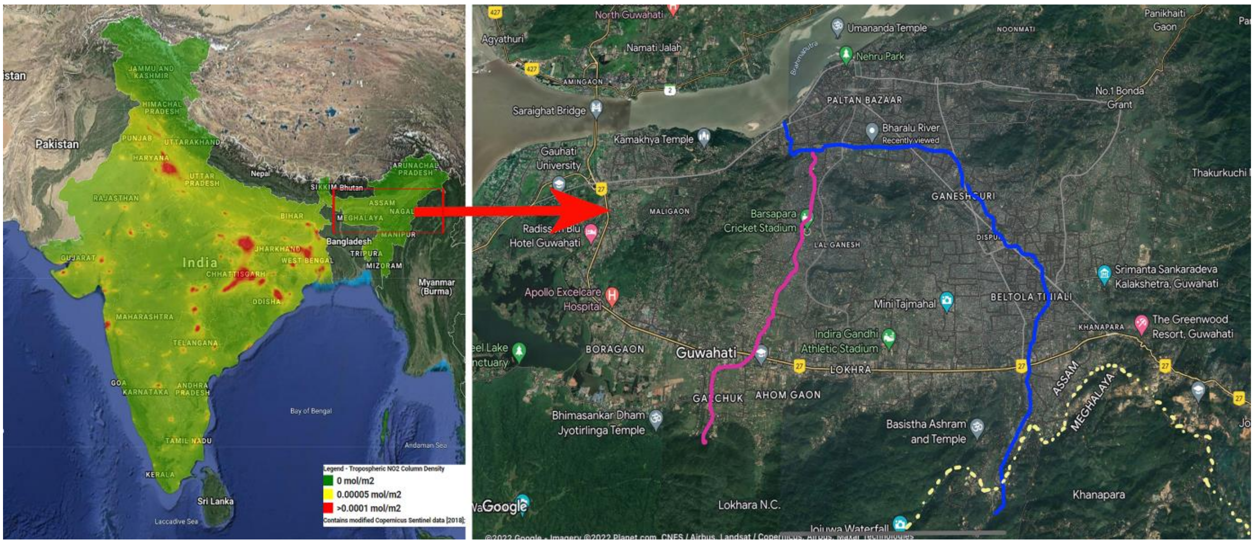
The Bharalu River, a key tributary of the Brahmaputra, plays a significant role in the overall water quality and pollution dynamics of the region [6]. As the Bharalu flows through the metropolitan city of Guwahati in Assam, it acts as a receiving body for the untreated sewage and wastewater discharged into it. Guwahati is the most important and highly populated city established alongside the Brahmaputra supporting a population of more than 1.2 million. The city is estimated to generate around 154 million litres daily which is directly discharged into the river mostly without treatment. The increasing population of the metropolitan, which has grown at an average annual rate of 20%, is aggravating the higher volume of sewage generated [7]. The untreated sewage and industrial effluents that enter the Bharalu River eventually find their way into the Brahmaputra River, exacerbating the pollution levels and impacting the downstream ecosystems and communities that rely on the Brahmaputra for various purposes. Notably, the Bharalu once used to be a pristine ecological water resource flowing through the city with the degradation happening in the past two and a half decades.

As such, this study aims to analyse the interrelationship between the ecological and economic aspects of the Bharalu River by introducing a novel index called the Ecology-Economy index (EEI). This index has been devised as a fundamental measure to assess the intricate dynamics between economic activities and ecological conditions in the Bharalu River watershed. By utilizing this index, the study seeks to capture and evaluate the level of integration and impact of economic development on the ecological quality of the Bharalu River ecosystem and further the cause for its urgent restoration.

2. Materials and Methods

2.1. Study Area

The study was carried out in the Bharalu river basin, which is situated between latitude 25°59' to 26°11' N and longitude 91°43' to 91°50' E. The river originates in the hilly catchment of Meghalaya and maintains its natural state until it enters the densely inhabited areas of Guwahati, which is part of Assam's Kamrup Metro District **(Figure 1)**. The Bharalu river stretches approximately 6.2 km in length, covering a total catchment area of about 120 sq. km. This catchment area is almost evenly divided between the hill region and the plains. Within the city of Guwahati, the river drains an area of around 12 sq. km. The study was conducted over a period from March 2020 to December 2022. For this study, extensive field data collected from 322 individual respondents were considered.



(Source: Google Earth ver7.3)

Figure 1. Satellite Map of Guwahati city *(Blue line indicates the Bharalu river)*

2.2. Mathematical Formulation

The conceptual framework of the Ecology-Economy Index (EEI) for the Bharalu river draws on principles from concepts of both economics and ecology **(Figure 2)**. As such, it consists of two primary components – the ecological indicator (e_i) and economic indicator (E_i), each having sub-indicators. The mathematical formulation is based on the concept of a weighted average index. The weights have been defined based on findings of an extensive field survey conducted by the researchers and assessing the findings using statistical techniques. Besides, the weights have also been subjectively assessed based on previous and contemporary literature as well as direct observation. The computational steps involve normalising the data for each indicator and their sub-indicators before calculating the index so that the data falls within a standard range, allowing them to be combined into a single index. Since each indicator can have different units and scales, normalizing these values allows us to make meaningful comparisons and aggregations. The Min-Max normalization method is used for this purpose, and it rescales the data to a fixed range of 0 to 1. The normalization equation is given by:

$$x' = \frac{x - min(x)}{max(x) - min(x)}$$

where x represents the original value, x' is the normalized value, and $min(x)$ and $max(x)$ are the minimum and maximum values of the variable, respectively. After normalization, each indicator shall be assigned a weight (w_i), based on its perceived importance. The final indicator (I) is computed as a weighted average of these normalized sub-indicators:

$$I = \frac{\sum_{i=1}^{n} w_i x_i'}{\sum_{i=1}^{n} w_i}$$

where n is the total number of sub-indicators, x'_i is the normalized value of the i-th indicator, and w_i is the weight for the i-th indicator.

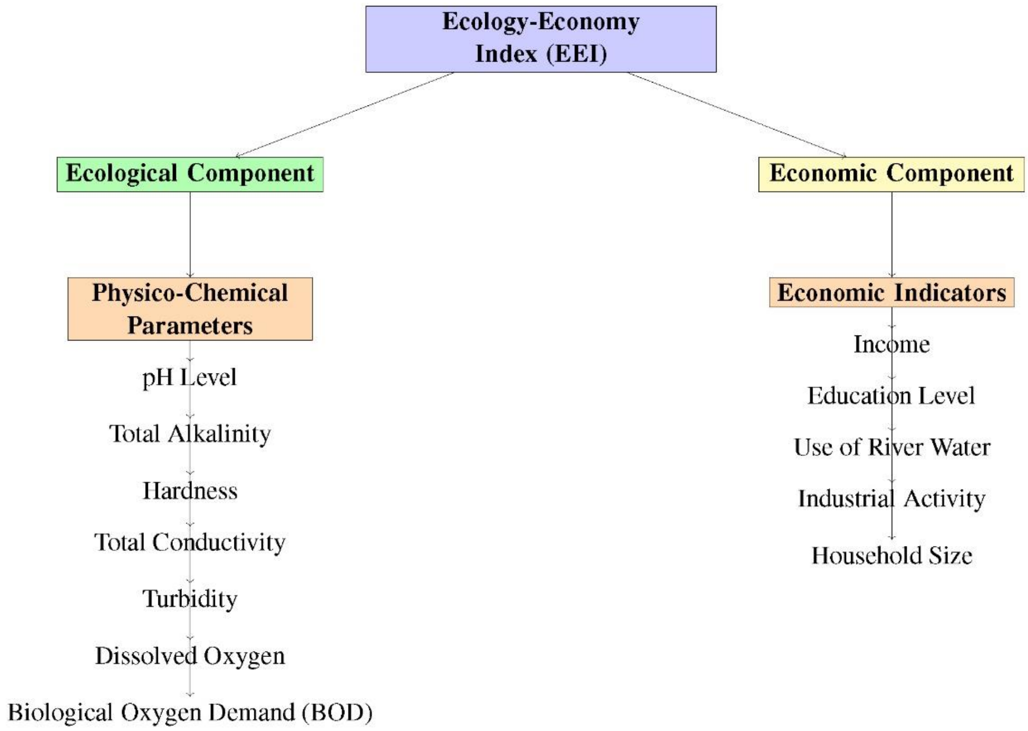


Figure 2. Conceptual framework of EEI (Source: Author)

The final step in calculating the EEI is to combine the normalized Ecological Indicator (*e*) and Economic Indicator (*E*) into a single index. This step involves assigning weights to the indicators to reflect their relative importance in the overall index.

Here, let us assume that the weight assigned to the Ecological Indicator (*ei*) is denoted as w_{ei}, and the weight assigned to the Economic Indicator (EI) is denoted as w_{EI}. The EEI is calculated using a weighted average approach:

$$EEI = w_{ei} \times ei + w_{EI} \times EI$$

Here, it is ensured that the weights w_{ei} and w_{EI} sum up to 1 (or 100%) so that the total weight assigned to the indicators is consistent. The index places a slightly higher weightage on the economic component (60%) compared to the ecological component (40%). The resulting EEI represents the integrated assessment of the ecology-economy relationship, considering both ecological and economic factors. It provides a single value that can be used for comparisons, monitoring, or decision-making related to the sustainable development of the Bharalu.

A lower index value (less than 0.5) suggests a very low interaction between the ecology and the economy, indicating minimal integration and coordination **(Table 1)**. However, as the index value increases, it indicates higher ratios which signifies a higher level of interaction between the ecology and the economy. In this context, a high ratio is considered undesirable as it implies that the economy has a significant impact on the ecology of the river.

Table 1. EEI index categories

Index value	Nature of interaction between ecology-economy
0 – 0.25	Low interaction
0.26 – 0.50	Moderate interaction
0.51 - 0.75	High interaction
0.76 – 1.0	Very High interaction

2.3. Ecological Indicators

To assess the ecological condition of the Bharalu river, water samples were gathered from three sites **(Table 2)** and analyzed for various essential physico-chemical parameters, including water temperature (WT), turbidity (TU), total alkalinity (TA), pH, total hardness (TH), conductivity (Cond.), dissolved oxygen (DO), and biological oxygen demand (BOD). The samples were collected from upstream, midstream, and downstream locations of the river, following standard procedures. Sampling was conducted during four seasons over the period from February 2020 to January 2021. The seasons were classified as pre-monsoon (March, April, and May), monsoon (June, July, August, and September), retreating monsoon (October and November), and winter (December, January, and February) [8].

Table 2. Sampling site locations

Site	Location coordinates	Name	Location nature
S1	26.0859° N, 91.7887° E	Ganesh Nagar, Basistha, Guwahati	Upstream
S2	26.1654° N, 91.7777° E	Nabin Nagar, Guwahati	Midstream
S3	26.1726° N, 91.7305° E	Bharalumukh, Guwahati	Downstream

2.4. Economic Indicators

The economic component of the index is built on the notion that the demographic and socio-economic characteristics of the riparian region directly or indirectly affect the ecological health of the river. First, the "Income" indicator represents the income level per annum of an individual. This indicator has been defined by three broad income categories that have been adapted from the categorization of the Ministry of Housing & Urban Poverty Alleviation, Government of India [9]. The "Education" indicator refers to the education level of the individual. Further, the "Use" indicator represents the pattern of usage of the Bharalu river's water. The "Industrial activity" parameter represents the level or intensity of industrialisation in the river basin. The data on industrial activity has been collected from the Pollution Control Board of Assam, the Statistical Handbook of the Government of Assam, as well as a field survey. It includes a number of sub-categories or indicators. Finally, the "Household size" indicator represents the size of the household of the respondent. It is categorised as: less than or equal to 2 members, between 3 and 5 members, between 6 and 8, 9 or above members. All economic indicators with their categories are enumerated in **Table 3**.

Table 3. Description of variables under the Economic Indicator component (Source: Author)

Economic Indicators					
Income		Education	Use	Industrial act.	Household size
Category	Income Range	Category	Categories	Sub indicators	Categories
Economically Weaker Section	Below INR 1 lakh	No schooling	Drinking	Employment	Less than 2 members
Lower Income Group	INR 1 lakh - 2 lakhs	Matriculation and below	Farming along the riverbank	Industrial Output	Between 3 – 5 members
Middle Income Group	INR 2 lakhs - 5 lakhs	Higher Secondary/Diploma education	Fishing	Energy Consumption	Between 6 – 8 members
Higher Income Group	INR 5 lakhs - 10 lakhs	Graduate degree	Household activities	Pollution Emissions	Above 9 members
	INR 10 lakhs - 15 lakhs	Post graduate degree & higher	Industrial & Manufacturing	-	-
	INR 15 lakhs and above	-	Irrigation	-	-
-		-	Mining	-	-
-		-	Swimming, washing & bathing	-	-

3. Results and Discussion

3.1. Pollution of the Bharalu River

Water pollution from industrial waste, untreated sewage, and agricultural runoff poses a significant issue in the Bharalu river. Studies have revealed elevated levels of heavy metals in the river, posing health hazards and threatening aquatic life [10]. The consequences of this pollution extend beyond health concerns and impact local industries as well. For example, the fisheries sector, a major source of income for many, is adversely affected by the deteriorating water quality. Decreasing fish populations and diversity due to pollution not only disrupt fishers' livelihoods but also negatively impact the state's economy [11].

Moreover, infrastructure development like dams and embankments has also left a mark on the river's ecology. These structures can alter the river's flow, disrupt the movement of aquatic species, and lead to habitat fragmentation. In the case of the Bharalu river, the construction of such structures may have contributed to the decline of migratory fish species, which play a vital role in the river's ecosystem and serve as a critical resource for local communities [12].

The tea industry, being a significant contributor to Assam's economy and a major employer, relies heavily on the health of the Bharalu river. River pollution can hamper the availability of clean water essential for irrigation and tea processing, consequently affecting tea production. Additionally, the degradation of the river system can disrupt the water cycle, potentially contributing to climate change and erratic rainfall patterns, further impacting the tea industry [13].

Given these pressing concerns, the degradation of the Bharalu river has become a critical and consequential issue. The river's health directly influences Assam's economy and the livelihoods of its people. To safeguard the river and its associated ecological and socio-economic value, it is imperative to implement sustainable and holistic river management strategies tailored to the unique challenges faced by the Bharalu river. Understanding and addressing the extreme ecological degradation in this significant tributary of the Brahmaputra River is of utmost importance in ensuring a better future for the region and its communities.

3.2. Status of the Ecological Indicators

Figure 3 showcases the trends of physico-chemical parameters observed during the course of the study. The pH values obtained during the physico-chemical assessment reveal interesting patterns in water acidity. Site S1 shows relatively stable pH levels around 7.3 to 7.5 throughout the monitoring period, indicating a near-neutral condition. In contrast, Site S2 exhibits a wider pH range, with values ranging from 3.6 to 5.5. The lower pH levels at S2 suggest acidic conditions, likely attributed to the high pollution levels reported at this site. Site S3 displays a more consistent pH range, fluctuating between 5.3 and 6.2. The slightly acidic pH values at S3 may be influenced by downstream factors. As such, the pH analysis illustrates variations in water quality along the Bharalu River, with Site S2 demonstrating the most significant deviation from the neutral pH and highlighting the impact of pollution on the river's acidity.

The turbidity values recorded in Site 1 shows relatively low turbidity levels, ranging from 32 to 46 NTU (Nephelometric Turbidity Units). These low turbidity values suggest that the water is relatively clear, with fewer suspended particles. On the other hand, Site 2 exhibits higher turbidity levels, ranging from 306 to 433 NTU. These elevated turbidity values indicate a higher concentration of suspended particles, which may be attributed to pollution or sediment run-off in this area. Similarly, Site 3 also presents moderate to high turbidity levels, varying from 125 to 252 NTU, suggesting the presence of suspended particles. The fluctuations in turbidity at all three sites may result from variations in sediment load, land use, and human activities along the river's course.

The total alkalinity data recorded range from 116 to 158 mg/L. These moderate to high alkalinity levels indicate that the river has the capacity to maintain a relatively stable pH despite potential acid inputs. Higher alkalinity values suggest the presence of alkaline substances like bicarbonates and carbonates, which can help neutralize acidic components and stabilize the water's pH. Besides, the recorded conductivity values range from 338 to 1020 μS/cm. Higher conductivity values generally indicate higher levels of dissolved ions and salts in the water, suggesting potential pollution or mineralization. The recorded hardness values range from 222 to 591 mg/L (milligrams per litre) as $CaCO_3$.

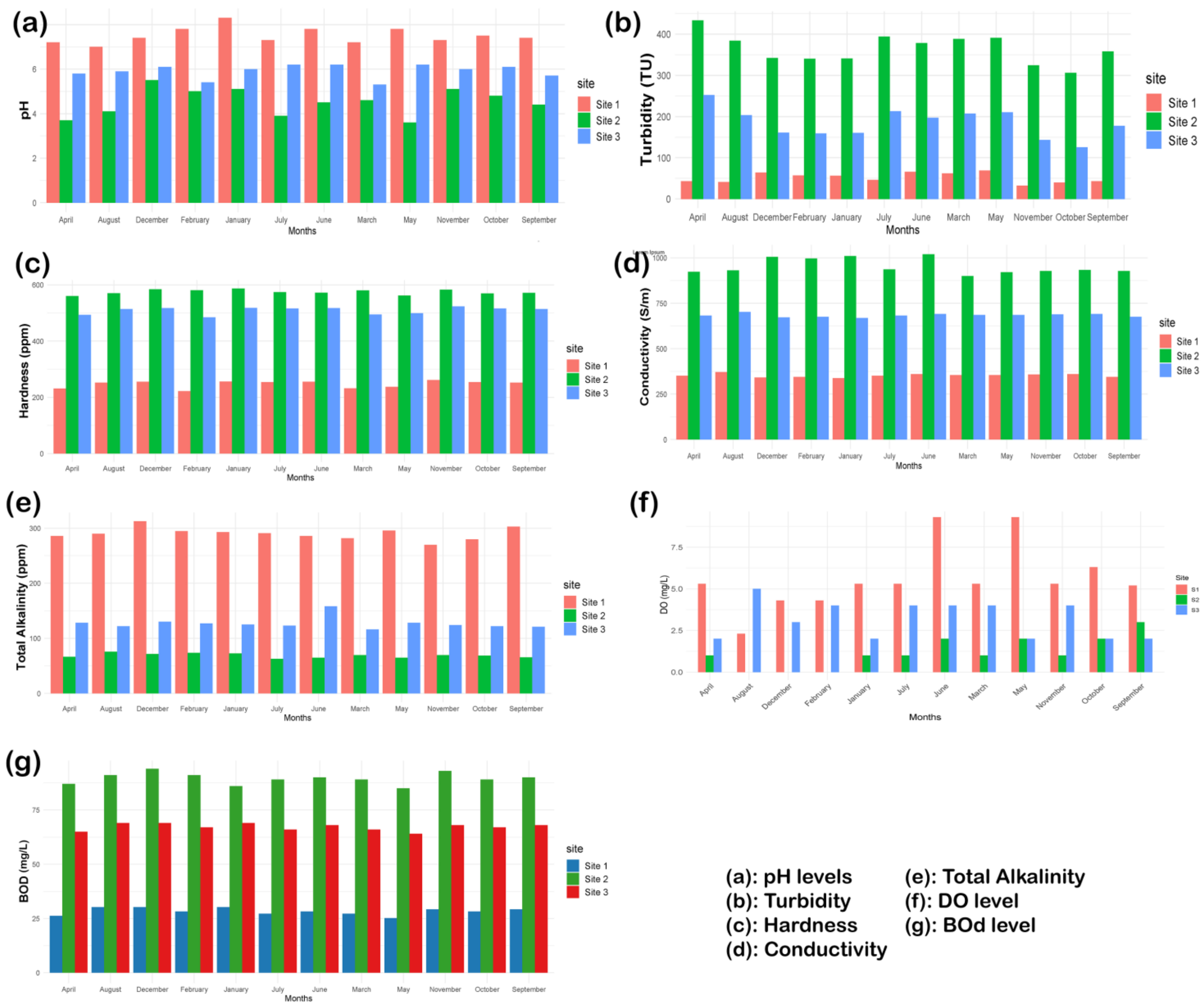


Figure 3. Trends of various physico-chemical parameters across three sample sites

One of the key indicators of pollution is the biological oxygen demand (BOD), which measures the oxygen required by micro-organisms to decompose organic matter in the water. The data shows relatively high BOD values ranging from 63 to 72 mg/L across all months. These elevated BOD levels indicate a substantial presence of organic pollutants in the Bharalu river. The highest BOD values are consistently observed during the pre-monsoon and winter seasons, particularly in December, January, and November. These months coincide with increased industrial and urban activities, leading to higher inputs of organic waste into the river. The presence of high BOD levels reflects the inadequate treatment of industrial and domestic wastewater, indicating the significant impact of industrial and urban pollution on the river's water quality.

The DO and BOD values provide crucial insights into the river's ecological health and the potential impact on aquatic life. DO is crucial for supporting aquatic life, as it is necessary for the respiration of fish and other organisms living in the water. From the data, we observe variations in DO levels among the three sample sites (S1, S2, and S3). Site 1 consistently shows relatively higher DO levels, ranging from 4.3 to 9.3 mg/L. In contrast, Site 3 consistently exhibits low or zero DO levels, indicating severe oxygen depletion in the water. Such a condition can occur due to the decomposition of organic matter by bacteria, leading to hypoxic or anoxic conditions. Site 3 shows intermediate DO levels, but it also experiences reduced DO in some instances, indicating moderate pollution levels. The lack of dissolved oxygen in Site23 suggests significant pollution, possibly from organic waste discharge, or other sources contributing to oxygen-demanding substances. This pollution can lead to adverse effects on aquatic ecosystems, including fish kills and reduced biodiversity. Therefore, the data indicates that the Bharalu River is experiencing pollution, particularly at Site 2, where low or absent DO levels signify a compromised environment for aquatic organisms.

Further, higher BOD values indicate a greater number of organic pollutants, which can result from various sources such as untreated sewage, industrial effluents, and agricultural runoff. Site 2 consistently exhibits the highest

BOD levels, ranging from 85 to 94 mg/L. Site 3 also shows relatively high BOD values, ranging from 64 to 69 mg/L. These higher BOD levels in Sites 2 and 3 indicate a significant presence of organic pollutants, which can lead to the depletion of dissolved oxygen and negatively impact the river's ecosystem. In contrast, Site 1 generally displays lower BOD values, ranging from 25 to 30 mg/L, suggesting comparatively lesser organic pollution. However, it is essential to note that even moderate BOD levels can stress the river's ecosystem and harm aquatic life. Therefore, the data indicates that the Bharalu River is experiencing heavy organic pollution, with Site 2 and Site 3 showing higher BOD levels, reflecting the impact of human activities on water quality.

Findings from all of these physico-chemical parameters suggest that their values exceed any existing permissible limits set by Bureau of Indian Standards (BIS) or any other such authorised standards from across the world.

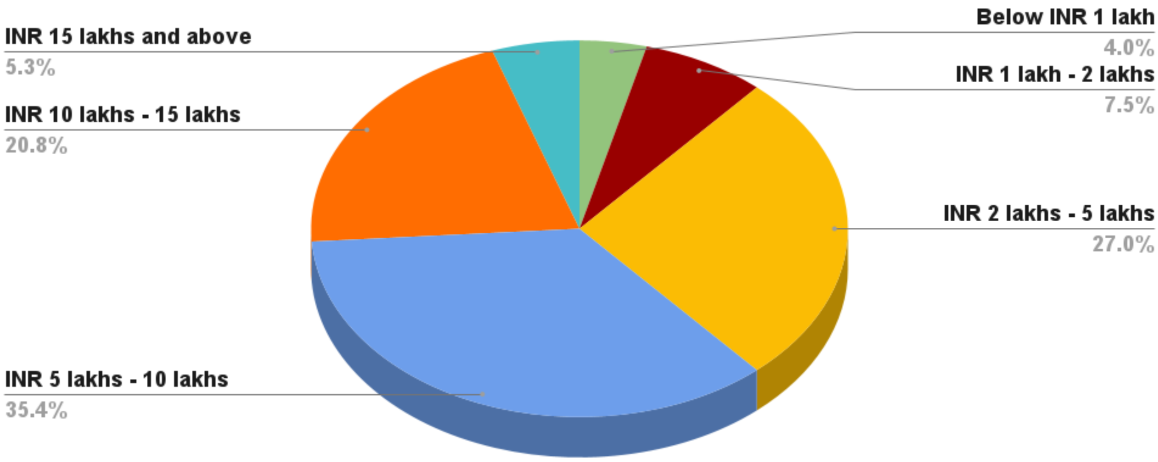
3.3. Discussion on the Economic Indicators

Income Indicator

Figure 4 provides a fascinating view into the income brackets of a given population, detailing the frequency and percentage of people within each income bracket, along with the most common level of education, and the minimum and maximum income within each bracket. Starting with the lowest income bracket, 'Below INR 1 lakh,' we see a frequency of 21, which represents 7% of the population. People in this bracket have no schooling as their most common level of education. The next bracket 'INR 1 lakh - 2 lakhs' contains a considerably larger segment of the population (81), comprising 27%. The most common level of education is primary education. A direct correlation between income and education level seems to emerge here. The income range for this category is approximately from INR 100,000 to INR 199,000, highlighting a significant jump in minimum income compared to the previous category. The income range for 'INR 2 lakhs - 5 lakhs' category (INR 200,450 - INR 499,293.6) further reinforces the direct relationship between income and education level. The highest income category, 'INR 15 lakhs and above,' is represented by 19 individuals or 6.41% of the population, with a postgraduate degree and higher as the most common level of education. The income range is from INR 1,506,600 to INR 1,999,002. It is interesting to note the representation gap between this category and the one before it, despite both categories having relatively advanced education levels. While there is a visible direct relationship between income and education levels for most categories, some interesting variations suggest other factors might be at play, such as skill specialization or potentially the influence of inheritance or entrepreneurship.

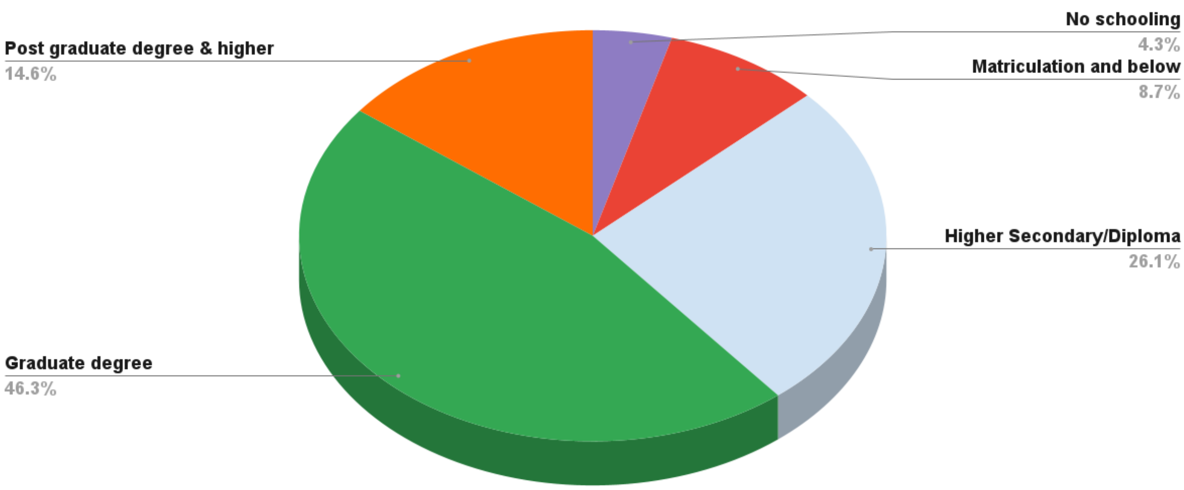
Education Indicator

The education level distribution of the respondents provides valuable insights into the educational demographics of the region **(Figure 5)**. Among the 322 participants, there is a significant representation of individuals with higher education qualifications, with 46.27% possessing graduate degrees and 14.60% having postgraduate degrees or higher. Approximately 26.09% of participants have completed higher secondary or diploma education, and 8.70% have educational qualifications up to matriculation or below. A noteworthy aspect is the representation of individuals with no schooling. Approximately 4.35% of the participants fall into this category, which adds another dimension to the study. Education is known to influence attitudes and behaviours towards the environment. Individuals with higher education levels tend to have a higher level of environmental awareness and understanding of ecological issues. In the context of the Bharalu River study, those with graduate and post-graduate education levels are more likely to contribute positively to river conservation efforts and engage in activities that protect and restore the river's ecological quality. Despite the prominence of highly educated participants, the dataset also highlights participation from diverse sections. This diversity underscores the significance of local knowledge and environmental consciousness within the community.



(Source: Field survey)

Figure 4. Income level distribution



(Source: Field survey)

Figure 5. Education level distribution

Use Indicator

The Bharalu River plays a crucial role in providing various services (ecosystem services) that are essential for the well-being and livelihoods of the communities residing along its banks (**Figure 6**). A detailed analysis of the data on activities undertaken around the river reveals the extent to which people depend on the river for different purposes.

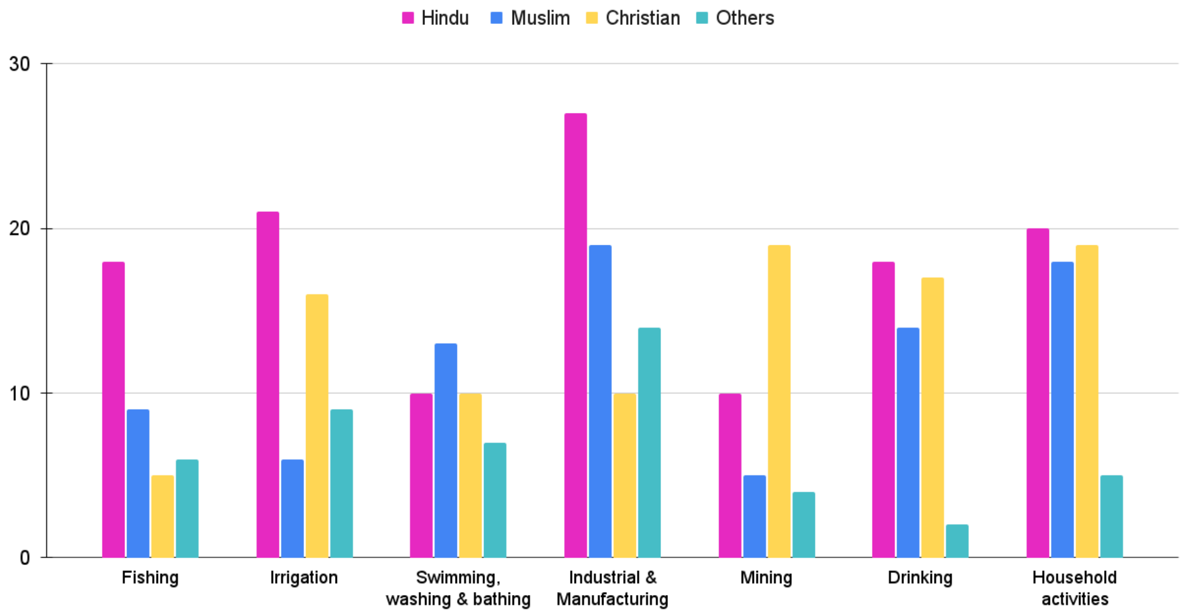
Findings reveal that one of the primary ecosystem services provided by the Bharalu River is drinking water. The data shows that a significant proportion of respondents, comprising 16.67%, 38.10%, 28.57%, and 16.67%, rely on the river for drinking water. This highlights the critical importance of the river as a source of clean and accessible drinking water for the local communities living mostly upstream. It is evident that a substantial number of people depend on the Bharalu River for meeting their basic water needs, and ensuring its quality and availability which is crucial for their well-being.

Farming along the riverbank is another activity closely associated with the Bharalu River. The data indicates that 17.95%, 58.97%, 17.95%, and 5.13% of respondents engage in farming activities along the riverbank. This signifies the role of the river in supporting agricultural practices and providing water for irrigation purposes. The high percentage of respondents involved in farming along the riverbank reflects the reliance of the local communities on the river for sustaining their agricultural livelihoods.

Fishing is another important activity associated with the Bharalu River, with 15.15%, 45.45%, 27.27%, and 12.12%

of respondents involved in fishing. This highlights the significance of the river as a valuable fishing ground, contributing to the local economy and providing a source of livelihood for the fishing communities. The percentage figures indicate the reliance of these communities on the river's fish resources, underscoring the need for sustainable management practices to ensure their long-term availability. Household activities, such as swimming, washing, and bathing, are also prevalent along the Bharalu River. The data reveals that 13.51%, 45.95%, 24.32%, and 16.22% of respondents engage in these activities. This signifies the importance of the river as a recreational and domestic water source for the local communities. The percentage figures demonstrate the significant role of the river in fulfilling the daily water-related needs of households, including personal hygiene and household chores.

Industrial and manufacturing activities account for 13.16%, 42.11%, 28.95%, and 15.79% of respondents engaged in such activities. This indicates the utilization of the river's resources for industrial purposes and highlights its role in supporting economic development and employment generation in the area. However, it also raises concerns regarding potential pollution and its impact on the river's ecosystem health and the well-being of the communities relying on it. Mining activities are also present along the Bharalu River, as indicated by 13.04%, 41.30% 28.26%, and 17.39%, revealing the exploitation of the river's mineral resources, which can have significant environmental implications if not properly managed. It is crucial to ensure responsible mining practices to minimize the negative impacts on the river's ecosystem and the communities dependent on it.



(Source: Field survey)

Figure 6. River water use distribution (community-wise)

Industrial Activity Indicator

The data provided in **Table 4** represents various industrial activity indicators for the Bharalu River watershed. The mean employment value of 576 indicates the average number of individuals employed in industries operating within the Bharalu River watershed. These employment figures suggest a significant industrial presence in the region contributing to its economic growth. However, it invariably raises concerns about the potential environmental consequences of industrial activities on the river. Along with this, the mean industrial output value of INR 770650 represents the average monetary value of production or output of industries in the study area. In our case, a higher monetary value of industrial output implies greater economic productivity, but it also indicates an increased consumption of resources and potential waste generation, which will adversely affect the river's water quality.

Table 4. Industrial activity statistics

Sub-indicators	Mean
Ind act Employment (in numbers)	576
Industrial output (in INR)	770650
Energy consumption (in kWh)	28677.906
Pollution emissions (in tCO_2e)	5675.447
Industrial investment (in INR)	640500

Further, the mean energy consumption value of 28677.91 kilowatt-hours (kWh) of electricity per year reflects the average energy usage by industries in the Bharalu River watershed. High energy consumption may lead to higher greenhouse gas emissions and other pollutants, contributing to environmental degradation and impacting the river's ecosystem. Additionally, the mean pollution emissions value of 5675.45 tCO_2e (tonnes (t) of carbon dioxide (CO_2) equivalent (e)) indicates the average emissions of pollutants from industrial activities per annum. Elevated pollution emissions can lead to water contamination and negative impacts on aquatic life and biodiversity in the river.

Finally, the mean industrial investment value of INR 640500 represents the average financial investments made in industrial ventures within the study area. Higher industrial investment signals potential growth in industries but also calls for responsible environmental practices to mitigate adverse effects on the river's ecological health which is also observed to be almost non-existent among industrial units. As a whole**,** the data highlights the importance of effectively managing industrial activities in the Bharalu River watershed. It signifies a high degree of industrial activity which can definitely be a stimulus for pollution of the river. However, further in-depth study is essential to analyse the precise ecological footprint of industries and ensure the long-term health and sustainability of the Bharalu River.

Household Size Indicator

As per **Figure 7**, in the first category, less than or equal to 2, the average household size is approximately 1.44. This category includes all households with 2 members or fewer, which typically comprises single-person households and couples without children. The mean suggests that the majority of households in this category may consist of single individuals, given that the mean is closer to 1 than 2. The next category, 'between 3 - 5,' has a mean household size of approximately 3.92. This group likely includes families with one or two children or multi-generational households (e.g., a couple living with a parent). The average indicates that households with around 4 members are common in this category.

Figure 7. Household size distribution (Source: Field survey)

The 'between 6 - 8' category has a mean of approximately 7.03. These are larger family units, which might include multi-generational families with several children, or households where extended family members live together. The mean size implies that households at the higher end of the range (around 7 or 8 members) are more typical in this category. Finally, in the '9+' category, the average household size is 11.6. These are extensive households, potentially encompassing large multi-generational families or other group living arrangements. The high mean indicates that these households often include more than just 9 members, with around 11 or 12 being more typical. This data provides valuable insights into household sizes, revealing the distribution and typical make-up of households within each category. However, understanding the social, cultural, and economic contexts behind these numbers would further enrich our interpretation.

3.4. Computing the Index

The EEI has been developed as a comprehensive measure to capture the complex interplay between economic activities and ecological quality in the Bharalu river watershed. The index draws upon principles from various international indices, such as the Environmental Performance Index (EPI), to ensure that the methodology aligns with established frameworks. These international indices have been valuable references in integrating economic and ecological indicators into a comprehensive assessment tool. Therefore, based on calculations of the indicators (**Table 5**), the EEI can be calculated as follows:

$$EEI = w_{ei} \times ei + w_{EI} \times EI$$

$$= 0.4 \times 0.760 + 0.6 \times 0.6644 = 0.304 + 0.3986 = 0.7026$$

Therefore, EEI reveals a value of 0.7026 which falls in the high interaction category. This high interaction index value of 0.7026 indicates a substantial relationship between the ecology and economy in the context of the Bharalu River. This finding suggests that economic activities are significantly influencing the ecological health of the river. However, it is essential to interpret this result cautiously, considering the negative connotation associated with the economy's impact on the ecology.

Factors such as higher household sizes, the pattern of water use, increased industrial settlements, and greater energy consumption by industries have led to this higher economic indicator value, ultimately increasing the interaction index. On the ecological part, the physico-chemical parameters have already displayed a higher pollution level invariably reflecting a high value for the ecological indicator. This thereby indicates significant pollution levels in the river system.

Considering the assumptions made regarding the data, the EEI indicates thus a positive interaction between the ecology and economy. The "positive interaction" between ecology and economy implies that there is a correlation or relationship between the ecological and economic factors being considered, and this correlation is described as positive. In other words, as one variable (e.g., the economy) changes, the other variable (e.g., the ecology) also changes in a positive direction. It is important to note that a "positive interaction" in this context doesn't imply a beneficial or desirable outcome. It simply means that there is a connection or association between the two factors, and the nature of this connection may have to be inferred by examining the trend of the data and the weights assigned in the index.

From the findings, we infer from this that the economy has a higher impact on the pollution of the river system, but this index does not outright indicate whether the effect is an adverse one. The nature of the impact can be determined implicitly though by the trend of data and the weights assigned. Nevertheless, the EEI can serve as a fundamental and novel index, providing insights into the ecology-economy relationship of not only the Bharalu River, but also any other river water resource. Since the index is the first and only one-of-its kind as well as it incorporates certain new dimensions that have not been included in any other index, we have designated it as a novel index. It covers both ecological and economic aspects of the river and its associated ecosystem services. Other existing indices cover exclusively only the ecology or economic parts. With further improvements, this index can become a valuable tool for assessing and monitoring the interplay between economic development and ecological sustainability for polluted river systems.

Table 5. Results from computation of indicators

Indicator	Original Value	Min	Max	Normalized Value	Weight
Ecological Indicator (ei)					w_{ei}
pH Level	7.2	6.8	7.8	0.5714	0.3
Total Alkalinity	100 mg/L	50 mg/L	150 mg/L	0.5	0.2
Hardness	200 ppm	100 ppm	300 ppm	0.5	0.2
Turbidity	10 NTU	0 NTU	20 NTU	0.5	0.1
Dissolved Oxygen	6 mg/L	4 mg/L	8 mg/L	0.5	0.1
Biological Oxygen Demand (BOD)	4 mg/L	1 mg/L	10 mg/L	0.375	0.1
Weighted Average				0.760	
Economic Indicator (*EI*)					w_{EI}
Income Level (INR)	30,000	15,000	50,000	0.5	0.3
Education Level	12 years of schooling	6 years	16 years	0.6667	0.2
Use of River Water	High use	Low use	High use	1.0	0.1
Industrial Activity	High acitvity	Low acitivity	High acitivity	1.0	0.2
Household Size	4 members	2 members	6 members	0.5	0.2
Weighted Average				0.664	

4. Conclusions

The ecology of any significant water resource is highly dependent on the regional economic development of the area which it drains. In this case, any water resource flowing through an urbanised area is highly likely to be impacted by the level of urbanisation more so in an adverse manner, unless proper measures are in place to negate adversities. This study made an effort to study the interaction between ecology and economics of the Bharalu river, which is a key tributary of the Brahmaputra, a major South Asian transboundary river. We observed that the Bharalu is suffering from a very high degree of water pollution with BOD levels ranging from 4.3 mg\L to 94 mg\L. The pH values indicated a more acidic quality of water with turbidity showing values up to 433 NTU. Further, on observations regarding dependencies on the river, inhabitants were found to be highly interacting with the river, more so in case of river water usage which included majorly household, industrial and mining activities. The mean pollution emissions of 5675.45 tCO_2e are indicative of high industrial emission levels. High energy consumption of 28677.91 kWh of electricity per year by industries further consolidates the fact. Overall, it is undeniable that the Bharalu basin is characterized by a high level of household and industrial economic activities, including commercial activities. Therefore, the EEI reveals a value of 0.706 which is indicatory of a high interaction between the ecology-economy in the Bharalu basin. This interaction, considering direct observation of the resource, can be concluded to have put highly adverse pressure on the ability of providing a high degree of ecosystem services by the Bharalu river. The river is in the brink of an ecological breakdown, thereby a point of no return. In this regard, it is essential to make urgent restoration measures so that the river is ecologically rescued and revived paving the way for sustainable development of the entire region.

Compliance with Ethical Standards

All ethical standards have been complied with during the study.

Competing Interests

There are no competing interests among the authors of the study.

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