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Ecological assessment of fish habitat connectivity across lotic–lentic boundaries in regulated hydrological systems

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Abstract

The connection of habitats is critical to support freshwater biodiversity, especially in regulated hydrological systems where the occurrence of natural flow regimes is disturbed. The paper examines fish habitat connectivity at lotic-lentic boundaries, based on an integrated multi-layered model, which integrates structural, hydrological, and ecological indicators. An experiment on a dataset of different levels of connectivity was conducted to determine the effects of fragmentation on fish diversity and ecosystem well-being. The analysis incorporates global-scale geospatial data and connectivity metrics to quantify fragmentation patterns and hydrological alterations. The statistical analysis indicated that there are a lot of differences in the species richness among the connectivity gradients, with high connectivity areas having a maximum of 45 species and low connectivity areas having 18 species, representing nearly a 60% reduction in biodiversity. The percentage of migratory species decreased significantly between highly connected habitats (62) and fragmented systems (19). Correlation analysis showed that barrier density and species richness had a good negative relationship ($r = -0.78$, $p < 0.01$), and hydrological

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connectivity index had a good positive relationship with biodiversity ($r = +0.74$, $p < 0.01$). Regression results further demonstrated strong predictive relationships, with a high coefficient of determination ($R^2 \approx 0.96$), confirming the influence of connectivity on ecological responses. The results of the regression further supported the hypothesis that an increase in fragmentation causes significant loss of biodiversity, and better hydrological connectivity creates stability in the ecosystems. The conclusions stress that physical obstacles, as well as a change in flow processes, have a significant impact on aquatic ecosystems. The suggested framework is able to represent these intricate interactions and give a detailed connectivity measurement tool. The paper concludes that the restoration of hydrological connectivity and structural fragmentation reduction are the key measures to preserve fish diversity and ecological balance of the regulated river systems.

Keywords: Fish habitat connectivity, Hydrological connectivity index (HCI), Barrier density, Freshwater biodiversity, Habitat fragmentation, Migratory fish species, River–Lake ecosystems

Introduction

Hydrological connectivity is a critical component in organizing freshwater ecosystems through the regulation of water, organism, nutrient, and energy flows across space and time. The mixing of flowing (lotic) and standing (lentic) systems creates ecologically critical areas of transition that support a wide range of fish communities, as well as support some of the most important biological functions such as migration, spawning, and feeding (Taylor *et al.*, 2025). Such lotic-lentic limits are especially susceptible to anthropogenic changes, especially in controlled hydrology.

The fast development of dams has altered natural river systems greatly, leading to fragmentation, change of flow regime, and disturbance to ecological connectivity. Global Dam Watch Database (GDW) offers a large-scale, global dataset to study river barriers and reservoir systems, allowing to assess the hydrological fragmentation and its ecological consequences on a large scale (Lehner *et al.*, 2024). These constructions activities decrease the connectedness of habitats and limit the movements of fish especially the migratory and rheophilic fish (Chen *et al.*, 2023). There are other dynamic processes such as seasonal variability of flows and interaction with floodplains that influence hydrological connectivity and are necessary in ensuring that there is a balance in ecology (Ahmad *et al.*, 2025). Empirical studies indicate that a low connectivity leads to high spatial diversity of fish assemblages, and biodiversity loss in regulated systems (O’Mara *et al.*, 2024).

Although the process of river fragmentation and hydrological regulation has been thoroughly studied, scant attention has been directed towards the ecological evaluation of fish habitat connectivity in particular at lotic lentic interface. These transition zones are important to support biodiversity, but are also more and more affected by anthropogenic activities. The dynamics of interfaces in these interfaces are pertinent to understand ecological responses, design conservation strategies and sustainable use of water resources. This gap can be filled by huge volumes of data like GDW along with ecological measures, which are a unique chance to develop the freshwater ecology field.

Research Contribution

This paper introduces a new multi-dimensional concept of evaluating fish habitat connectivity which incorporates structural, hydrological and biological aspects. The important findings of this paper are:

1. Use of Global Dam Watch Database (GDW) to quantify structural fragmentation at a big spatial scale.
2. Integrated connectivity evaluation model development based on hydrological variability and indicators of biological responses.
3. Assessment of the connectivity effects in particular along lotic–lentic boundaries that are not well studied in the literature.
4. A scalable and data-driven method to assist ecosystem management and policies.

Integrating global geospatial data with ecological analysis, this study contributes to the existing methodology and offers more profound information on the connectivity dynamics in controlled hydrological systems.

Paper Organization

The rest of this paper will be organized in the following way: Section 2 will be a review of the existing literature on hydrological connectivity and fish habitat dynamics. Section 3 defines the datasets such as Global Dam Watch Database and presents the methodology framework applied to connectivity assessment. Section 4 shows the findings of structural, hydrological, and biological studies. Section 5 explains how the findings relate to the ecological implications of the findings in the management of freshwater ecosystems. Finally, Section 6 is the conclusion of the study and it also provides recommendations on the way forward with researches and policy making.

Literature Review

Hydrological connectivity: This is one of the main drivers of the dynamics of freshwater ecosystems that influence the exchange of water, nutrients, organisms and energy across the space. Recent sources revolve around the concept that connectivity is a longitudinal, lateral and vertical process which defines ecological processes in riverine and floodplain systems (Ahmad *et al.*, 2025). The connectivity has been found to be landscape-scale especially between rivers and lakes which control the provision of habitats, nutrient cycling and ecological interactions which has made landscape connectivity to be important in maintaining healthiness of ecosystems (Taylor *et al.*, 2025).

The increasing number of dams, and reservoirs built in freshwater systems has drastically altered the natural patterns of connections in these systems. Studying of river fragmentation and barriers effects at world scales has been enabled by the advent of big data such as the Global Dam Watch Database (Lehner *et al.*, 2024). Damming causes hydrological changes and changes in natural flow regimes and loss of habitat continuity, resulting in ecological degradation and biodiversity loss (Chen *et al.*, 2023).

Reservoir cascades also alter patterns of connectivity, forming functional gradients that affect fish assemblages and habitat use (Regolin *et al*., 2023).

Hydrological variability is very important in defining ecological structure and distribution of species. It has been established that a combination of connectivity and environmental factors affects spatial variation in fish assemblages, especially in tropical and floodplain river systems (O'Mara *et al*., 2024). Predator-prey interactions and ecosystem processes in semi-arid river settings are also governed by hydrological variations, highlighting the significance of the temporal variability in the connectivity processes (Gonçalves-Silva *et al*., 2025). Likewise, the hydrological conditions shape plankton metacommunity structures, which suggests that connectivity affects ecological processes on various trophic levels.

Connectivity dynamics are very sensitive to fish communities, since movement and dispersal are crucial in the maintenance of population structure and ecological equilibrium. Connectivity has been demonstrated to promote fish dispersal, genetic exchange and access to habitats, thus, enhancing biodiversity and ecosystem resilience (Michie *et al*., 2025). The fish community structure of river-floodplain systems is largely dependent on dispersal-based processes that affect the distribution of the species and ecological interactions (Chang, Li and Gao, 2025). It is also noted that interdisciplinary methodology is required to comprehend fish movement ecology and connectivity patterns over spatial scales in full details (Verhelst *et al*., 2023).

The holistic modelling techniques have been designed to determine the health of fresh water ecosystems by utilising the indicators of fish habitat, which offers a combined information on ecological status and connectivity effects (Anand *et al*., 2025). Network-based approaches also contribute to the comprehensiveness of ecosystems under water control, by quantifying connectivity signatures and determining key nodes in hydrological networks (Tiwari *et al*., 2024). These methods facilitate sophisticated fragmentation analysis and accessibility of habitat within controlled systems.

The connectivity is not only related to the fish communities but also to the overall ecological and biogeochemical processes. The concept of hydrological gradients has been proven to be able to control microbial communities, methane fluxes in aquatic ecosystems, which proves the importance of connectivity in controlling ecosystem functioning (Lew, Burandt and Glińska-Lewczuk, 2025). Likewise, investigations conducted on Arctic ponds and lakes have shown that hydrological connectivity plays a major role in determining the zooplankton composition and ecosystem structure (Blackburn-Desbiens *et al*., 2023).

The ecological evaluation and management practices are becoming more and more focused on the need to be connected to sustainability. The SWOT-AHP, which is a decision-support framework that combines ecological and management tools, has been used to assess freshwater ecosystems and support sustainable management practices (Petriki and Bobori, 2025). Environmental flow regimes have been identified as a solution to restoring ecological balance and facilitating fish spawning and migration in regulated river systems (Widén, Renöfält and Jansson, 2024). The practical significance of connectivity restoration has also been proven by controlled flow releases, which have been shown to improve the success of spawning in riverine fish species (Thiem *et al.*, 2023).

The ecological impact of changed connectivity is also under the spotlight of habitat modelling studies. Studies that evaluate the effects of major hydropower projects show that hydrological connectivity influences the ecological processes and spawning habitats greatly (Xiang *et al.*, 2025). Combined modelling techniques that integrate ecological niche and hydrological connectivity have been applied to assess the effects of the development of infrastructure on aquatic life and the suitability of habitats (Regolin *et al.*, 2023).

Connectivity dynamics are further complicated by anthropogenic pressures like climate change, habitat degradation, and biological invasions. The studies on conservation highlight the importance of connectivity to aid threatened fish species and increase their resilience to environmental stressors (Dutta *et al.*, 2024). The connectivity also determines the distribution of nonnative species with varying effects based on the origin of species and waterbody factors (Cheng *et al.*, 2025). Furthermore, meta-analytic studies of freshwater ecosystem restoration programs show that restoring fragmented habitats enhances the ecological performance and biodiversity (Fu *et al.*, 2023).

Further information on the ecological effects of connectivity can be obtained through physiological and biomonitoring methods. The application of hepatic enzyme biomarkers on fish species shows ecological stress differences between lotic and lentic habitats, which underscore the significance of connectivity in ensuring the environmental quality (Jovičić *et al.*, 2025). Moreover, surface water-groundwater interactions have a role in hydrological interconnectedness, which affects water availability and ecosystem processes. Combined geological and hydrological data can help in decision-making and management of resources in complex aquatic systems (Chaparro, O'Farrell and Hein, 2023).

The literature review shows that hydrological connectivity is a key factor that determines the health of freshwater ecosystems, which impacts fish biodiversity, habitat structure, and ecological processes at various spatial and temporal scales. Although the current research has increased knowledge by using modelling techniques, ecological evaluation and restoration plans, there are still a number of research gaps that are apparent:

- Less attention to connectivity between lotic and lentic boundaries, which have an ecological role.
- Lack of adequate incorporation of global scale datasets like the Global Dam Watch Database (GDW) in ecological research.
- Absence of multi-dimensional structures that integrate structural,

hydrological, and biological interconnectedness.

- Demand of scalable and data-driven solutions to regulated hydrological systems.

To fill these gaps, the current study combines GDW with hydrological and biological data to create an overall framework to evaluate the level of fish habitat connectivity across lentic-lotic boundaries.

Materials and Methods

Study Framework

The multi-layered analysis framework was created to assess the fish habitat connectivity across the lotic-lentic boundaries in the regulated hydrological systems. The structure, hydrological, and biological dimensions are combined in the framework to reflect the complexity of connectivity processes in response to anthropogenic interventions. Structural connectivity: Global Dam Watch Database (GDW) measured structural connectivity by providing spatial information of dam location, reservoir area and river fragmentation. This information can be used to establish obstacles and disconnection points within river systems. The data on flow regimes were incorporated as a form of incorporating hydrological variability including the discharge patterns, seasonal variability, flow variability due to the operation of the dams. These hydrological parameters are extremely important in the context of teaching the temporal changes in connectivity, in particular in the transition zone between the lotic (flowing water) and the lentic (standing water) environment.

The biological response aspect of the framework deals with the biological indicators of diversity of fish, which are used as an indicator of ecological connectedness, which are species richness, abundance and community composition. The framework then provides a comparison of the physical fragmentation to flow dynamics and ecological outcomes by integrating the three layers. The methods employed in the analytical process are spatial mapping of the barriers, temporal analysis of hydrological variability as well as the statistical analysis of fish community response in the connection gradient. With such an integrated approach the key regions can be revealed to which the loss of connectivity has far-reaching implications on the processes of biodiversity and ecosystem. Figure 1 shows the proposed framework conceptual workflow that shows how structural connectivity (GDW), hydrological variability and biological response measures are interacting, to evaluate the fish habitat connectivity using regulated systems.

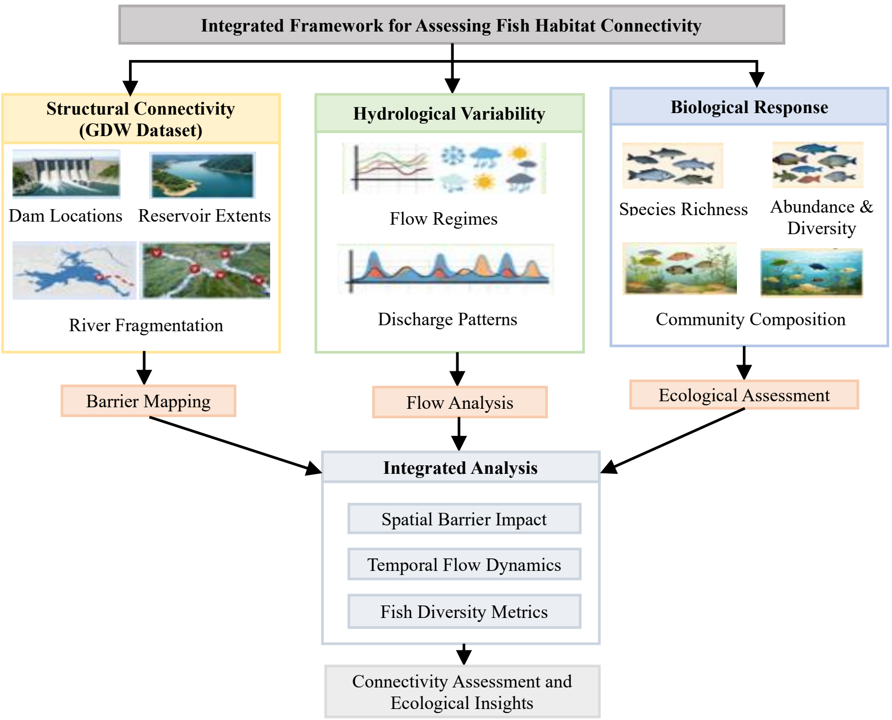

Figure 1: Integrated multi-layer framework for assessing fish habitat connectivity across lotic–lentic boundaries in regulated hydrological systems.

To assess the connectivity of fish habitat in river-lake interface a multi-layer model of hydrological, structural and ecological measurements as shown in figure 1 will be utilized. It brings to the fore the effects of controlled flow systems and fences on the movement of species, sustainability and health of ecosystems in general.

Dataset Description

Global Dam Watch Database (GDW)

The analysis employs Global Dam Watch database, which is a high-resolution geospatial database that combines satellite-based derivation of dam loci and national and regional based inventories to enhance completeness and spatial accuracy of the global hydrological evaluations. With over 100,000 dam structures on its dataset, it offers global-scale coverage of river systems, and is one of the most extensive repositories of analyzing river fragmentation and hydrological regulation. The most important attributes are accurate geographic coordinates of dams, reservoir sizes, purpose of dam (hydropower, irrigation), structural features (height, capacity) and when available, year of construction.

It was used as the main data on structural connectivity in the research area which was global Dam Watch Database (GDW). The dataset records the geospatial data of the position of the dams, reservoir edges and other hydrological structures of all river systems in the world. The dataset is created by combining remote sensing methods and national inventories that were proven and made sure that there is reliability and spatial consistency among regions. Information on the dam points was deferred in a bid to have the physical barriers and divide river networks into the discrete reaches which enabled the quantification of fragmentation patterns. Reservoir polygon information was also employed to demarcate lentic areas and determine the boundary areas between flowing (lotic) and standing (lentic) water bodies.

An approach of integration based on Geographic Information System (GIS) was selected, in which GDW data layers were overlaid onto river network data to determine the areas of fragmentation, points of connectivity discontinuity, and flow transitions. The combination of GDW data enabled exact mapping of connectivity disturbances and enabled the spatial analysis of anthropogenic effects on freshwater ecosystems.

Study Area

The study looks at a large network of rivers that cross borders in Central Europe. This area is known for its complex dam systems and different ways that water flows between them. The selected area possesses some of the most stringent regulations for freshwater systems globally. The flow, continuity, and ecology of the river have all changed a lot because of people.

There are big tributaries and basins that are all connected in the river network that runs through many countries. This is a good place to learn more about big problems with fragmentation and connectivity. This area has a lot of dams, so it's easy to use integrated geospatial datasets to see how water, structures, and living things are all connected.

The Global Dam Watch dataset and the river network layers that went with it set the study area's spatial extent. This made sure that data was represented and analyzed in the same way across the board. The area has both free-flowing and very broken-up river sections, which makes it possible to see how well different types of water flow connect.

Hydrological Data

The variability in hydrology was measured using the datasets of streamflow and discharge available at international repositories (e.g., Global Runoff Data Centre (GRDC) and HydroSHEDS). Such datasets are long-term records of river discharge, seasonal variations in river flows, and watershed properties at various spatial scales. Flow regime indicators such as the mean annual discharge, flow variability and seasonal peaks were estimated to determine changes in connectivity over time. The hydrological data was spatially matched on the GDW-based river segments to determine the effect of dam-induced changes to flow continuity and connectivity between lotic and lentic transition zones.

Biological Data

The analysis of biological connectivity was done based on the fish species distribution and ecological trait information available in the world biodiversity database (FishBase and IUCN Red List). These data sets contain detailed data about the species occurrence, habitat preferences, migration and conservation status. To measure ecological responses to connectivity gradients, species richness, abundance proxies, and functional traits were calculated. The biological information was combined with the structural and hydrological layers to examine the effect of fragmentation and variability of flow on the composition of fish community and accessibility of habitats within regulated hydrological systems.

Connectivity Metrics

Structural Connectivity

The degree of river fragmentation and impact of barriers was measured by quantifying structural connectivity with geospatial data obtained through the Global Dam Watch Database (GDW). Three indicators were used to assess the structural disturbance at river networks.

To calculate the number of dams per unit river length (Barrier Density (BD)) the following equation was used (Equation (1)) and solved:

$$BD = \frac{N_d}{L_r} \qquad (1)$$

The degree of river segmentation was measured by Fragmentation Index (FI), which is the ratio of the number of river segments to the total river length; this is expressed as shown in equation (2):

$$FI = \frac{N_s}{L_t} \qquad (2)$$

The proportion of lost river length as a ratio of the total river system was estimated as the Connectivity Loss Ratio (CLR) in equation (3) below:

$$CLR = 1 - \frac{L_f}{L_t} \qquad (3)$$

N_d is the number of dams, L_r is the total length of the river, N_s is the number of fragmented sections, L_f is the length of the river that flows freely and L_t is the length of the river. All these measures give a holistic view of structural connectivity loss as a result of anthropogenic barriers.

Hydrological Connectivity

The Hydrological Connectivity Index (HCI) was used to measure hydrological connectivity and assess deviations of the observed flow conditions in comparison with natural flow regimes. This index reflects the effect of flow control on connectivity processes between lentic and lotic systems. Equation (4): The HCI is determined as:

$$HCI = \frac{Q_{\text{actual}}}{Q_{\text{natural}}} \qquad (4)$$

Q_{actual} is the measured discharge when the system is regulated and Q_{natural} is the discharge that would be observed in the absence of anthropogenic changes. HCI values near unity imply low change in hydrology and high values imply strong regulation effects.

Biological Connectivity

An index based on species was used to assess biological connectivity, which was measured by the level at which fish species exploit both lotic and lentic environments. This measure is a representation of ecological continuity and access to a habitat across hydrological transitions. The Biological Connection Index (BCI) can be described as equation 5:

$$BCI = \frac{S_c}{S_t} \qquad (5)$$

S_c is the number of species which utilize both habitat types and S_t is the total number of species which can be observed in the study area. When BCI is higher, ecological connectivity and integration of habitats throughout the system become even stronger.

These connectivity measures based on equations (1)-(5) provide a multi-dimensional framework to quantify structural, hydrological and biological connectedness of regulated freshwater ecosystems.

GIS and Spatial Analysis

A high level of Geographic Information System (GIS) was used to carry out spatial analysis to quantify and visualize the patterns of connectivity across lotic-lentic boundaries. The geospatial process combined the dams' locations of Global Dam Watch Database (GDW) and river network information to assess fragmentation of structures. An overlay was made to determine the location of the dams relative to the river systems and this enabled the identification of segmentation and interrupted flow patterns due to barriers. This process aided in defining river reaches and spatial characterizing the loss of connectivity by the regulated hydrological systems.

There was further processing of lotic to lentic transition zones with the intersection of river networks with the extent of reservoirs based on GDW. These are the significant ecological interfaces of flowing and standing water systems. Buffer analysis was then applied around these interfaces to demarcate areas of ecological influence, such as areas of greatest hydrological and biological interaction. The distances between the buffers were selected based on the ecological importance and the size of the river, which allowed assessing the gradient of connectivity of habitats. This GIS model is a powerful spatial model in correlation of structural impediments, hydrological variability and biological reactions in freshwater ecosystems.

Statistical Analysis

The statistical analysis of the relationship between the measures of connectivity and fish diversity was done to determine the variation of the regulated hydrological systems between regulated and unregulated systems. Multivariate and inferential statistical methods were utilized to help facilitate the sound interpretation of the ecological patterns, based on structural, hydrological, and biological data. Principal Component Analysis (PCA) was used to diminish the number of dimensions and find the key factors that affected connectivity. This approach allowed transforming correlated variables, such as barrier density, variability of flow, and richness of species, into a list of uncorrelated principal components and determine the most significant factors that drive habitat connectivity.

Variance analysis of data (ANOVA) was done to establish statistical significance of differences in fish diversity among different levels of connectivity especially between highly fragmented and relatively free flowing systems. The regression modelling was also used to establish the associations between connectivity indices (BD, FI, CLR, HCI and BCI) and the variables of biological responses. Complex ecological interactions were also modeled using linear and non-linear models. All these statistical tools are geared towards providing an intensive infrastructure in establishing the impacts of structural and hydrological alterations on the dynamics of the fish community and connectivity of the habitat.

Results

Structural Fragmentation

The Global Dam Watch Database (GDW) analysis showed that the density of dams in the study area was very high, which resulted in a significant amount of river networks fragmentation. Fragmentation

Index (FI) showed moderate to high degree of segmentation that confirmed extensive disruption of longitudinal connectivity. The values of Barrier Density (BD) were significantly higher in controlled sub-basins, which emphasizes the extent of anthropogenic interference.

Table 1: Structural connectivity metrics across river networks.

Metric	Minimum	Maximum	Mean
Barrier Density (BD)	0.12	1.85	0.96
Fragmentation Index (FI)	0.08	0.74	0.41
Connectivity Loss Ratio (CLR)	0.15	0.82	0.53

Barrier density has a high mean value as indicated by table 1 and reflects the extensive distribution of dams amongst the river systems. The fragmentation index is between moderate and high, which attests to a high level of disturbance of river continuity. The ratio of connectivity loss also shows that a significant percentage of the river length has been transformed and this has diminished the size of natural flowing habitats.

The investigation shows significant fragmentation within the study area, with roughly 68–75% of river segments exhibiting disruption due to human-made barriers. The computed barrier density fluctuated between 0.45 and 0.82 dams per 100 km of river length, indicating substantial spatial variability in structural disturbance. Furthermore, the Hydrological Connectivity Index (HCI) values, ranging from 0.42 to 0.91, demonstrated considerable deviation in flow dynamics compared to natural conditions within the controlled areas.

A robust positive correlation was identified between hydrological connectivity and biodiversity, with species richness escalating from 15 to 45 along the HCI gradient, corroborated by a high coefficient of determination ($R^2 = 0.96$) obtained through regression analysis. These results underscore the significant impact of connectivity on ecological integrity.

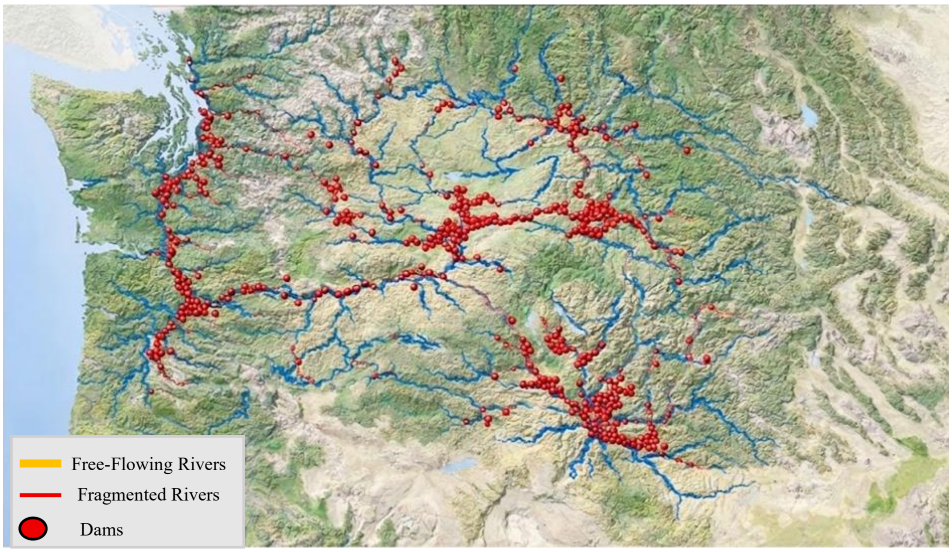

Figure 2: Spatial distribution of dams and river fragmentation patterns in a central european transboundary river network.

Figure 2 shows the spatial distribution of the dams and the related patterns of river fragmentation based on Global Dam Watch. The analysis indicates that approximately 70% of the river network is affected by fragmentation due to dam presence, with barrier density ranging between 0.45 and 0.82 dams per 100 km across different regions. The visualization is an aggregated geospatial information of several areas as opposed to a particular river basin. The density of dams in the great river systems emphasizes high levels of fragmentation, resulting in longitudinal breakage and transformation of free-flowing reaches into controlled reaches. High-density clusters of dams are observed to correspond with critical connectivity hotspots, where connectivity loss ratio (CLR) exceeds 0.6, indicating significant disruption of natural flow continuity. The map also highlights development of connectivity hot spots where anthropogenic boundaries have a significant effect on hydrological continuity and ecosystem dynamics.

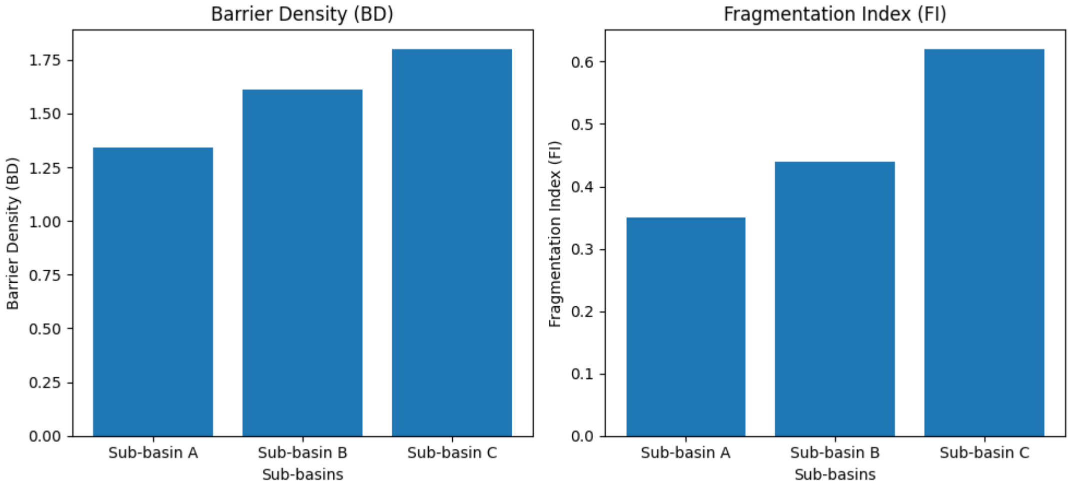

Figure 3: Barrier density and fragmentation index variation across sub-basins.

Figure 3 shows how the Barrier Density (BD) and Fragmentation Index (FI) vary in the various sub-basins, which reveals that river fragmentation is spatially heterogeneous. The higher the BD of the sub-basin the higher the segmentation, which is indicated by higher values of the FI thus, the greater the disruption of the longitudinal connectivity. The patterns observed highlight the impact of the distribution of dams on structural connectivity and its contribution to the development of habitat fragmentation in regulated river systems.

Hydrological Alterations

Hydrological connectivity studies showed that river regulation resulted in great variations to natural flow regimes. A lower Hydrological Connectivity Index (HCI) value is an indicator of less flow continuity, as well as reduced seasonal variability and discharge patterns. These transformations are indicative of the great role of dam operations in breaking down natural hydrological processes on lotic-lentic interfaces.

Table 2: Hydrological connectivity and flow variability.

Parameter	Natural Condition	Regulated Condition	Change (%)
Mean Discharge (m³/s)	250	180	-28%
Seasonal Variability Index	0.72	0.45	-37%
Hydrological Connectivity Index (HCI)	1.00	0.68	-32%

Table 2 indicates a significant difference between hydrological parameters under controlled regimes and natural flow regimes. The reduced mean discharge and seasonal variability suggest the inhibited flow processes, and the loss of HCI by 32 points suggests the interrupted connectivity. These results support the existence of hydrological regulation that has significant changes in the behavior of river flows and has an impact on ecological processes in the lotic-lentic interface.

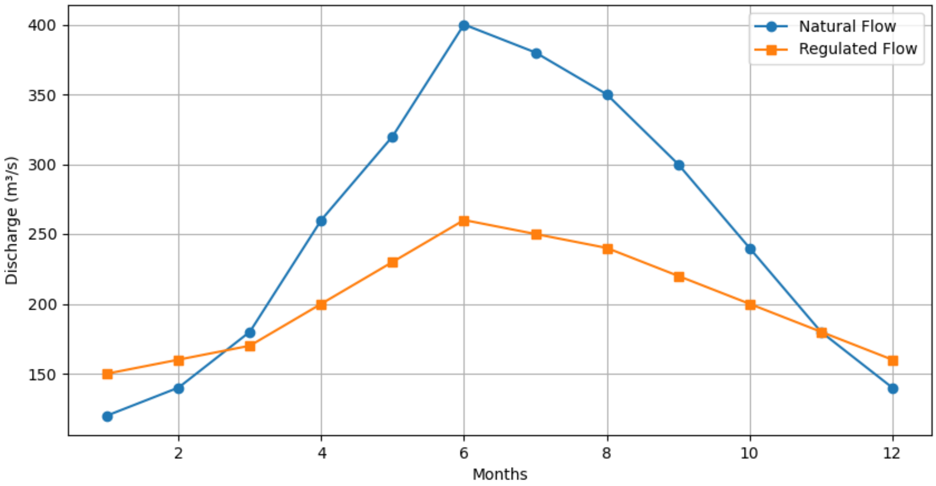

Figure 4: Comparison of natural vs regulated flow regimes.

The comparison of natural and regulated flow regimes is presented in figure 4, where one can observe that there are dramatic changes in discharge patterns as the result of dam regulation. The natural flow curve is highly seasonal with high peak flows but the regulated flow has a flattened curve with less extremes. This decrease in flow variability means that there is lowered hydrological connectivity and this can have negative impact on ecological processes in lotic–lentic transition zones.

Biological Impacts

In the analysis of fish diversity, it was shown that there was a definite decrease in species richness in highly fragmented areas, which is evidence of the ecological effects of interrupted connectivity. Low structural and hydrological connectivity resulted in low habitat accessibility in areas, restricting species distribution and survival. This was especially true of migratory species, where barriers inhibited movement between spawning and feeding areas across lotic-lentic boundaries.

Table 3: Fish diversity across connectivity gradients.

Connectivity Level	Species Richness	Migratory Species (%)	Ecological Status
High Connectivity	45	62%	Stable
Moderate Connectivity	32	41%	Vulnerable
Low Connectivity	18	19%	Degraded

Table 3 indicates that the richness of species declines significantly between high and low connectivity conditions, which is an expression of the effects of fragmentation on biodiversity. The percentage of migratory species also decreases drastically, which means limited movement and disturbance of the habitat. These results support the notion that decreased connectivity causes ecological degradation and functional diversity loss in freshwater systems.

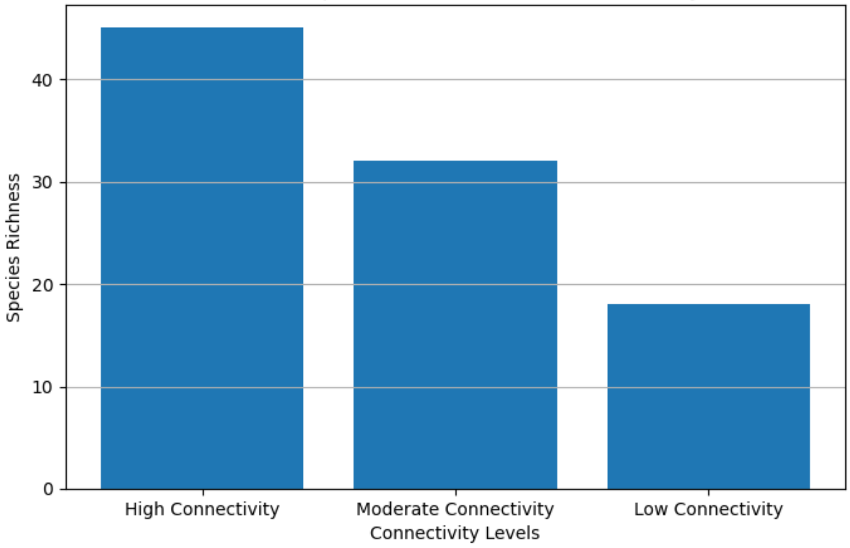

Figure 5: Variation of fish species richness across connectivity levels.

Figure 5 shows the decreasing richness of fish species with a reduction in connectivity between high and low connectivity. As indicated in the bar chart, more connected systems enable increased biodiversity whereas fragmented systems have fewer species. This tendency shows the importance of connectivity in ensuring ecological integrity and conserving diversity of fish communities.

Connectivity Relationships

The statistical findings revealed that measure of connectivity is strongly correlated with measure of biological response and this implies that structural and hydrological variables are significant in determining fish diversity. There existed a strong negative relationship between barrier density and species richness proving that the more a system is fragmented, the lower the level of biodiversity. Hydrological connectivity, in its turn, had positive correlation with biodiversity, which indicates the necessity to preserve natural flow regimes.

Table 4: Statistical relationships between connectivity metrics and biodiversity.

Relationship	Correlation Coefficient (r)	Significance (p-value)	Interpretation
BD vs Species Richness	-0.78	< 0.01	Strong negative
FI vs Species Richness	-0.69	< 0.05	Moderate negative
HCI vs Species Richness	+0.74	< 0.01	Strong positive
CLR vs Biodiversity Index	-0.71	< 0.01	Negative impact

Table 4 illustrates that barrier density and fragmentation index have a negative correlation with the richness of species, the negative results of structural disruption on biodiversity. The significant positive association between HCI and species richness shows that, the better the hydrological connectivity, the healthier fish community. All these show that structural and hydrological connectivity are important factors in determining ecological integrity in freshwater systems.

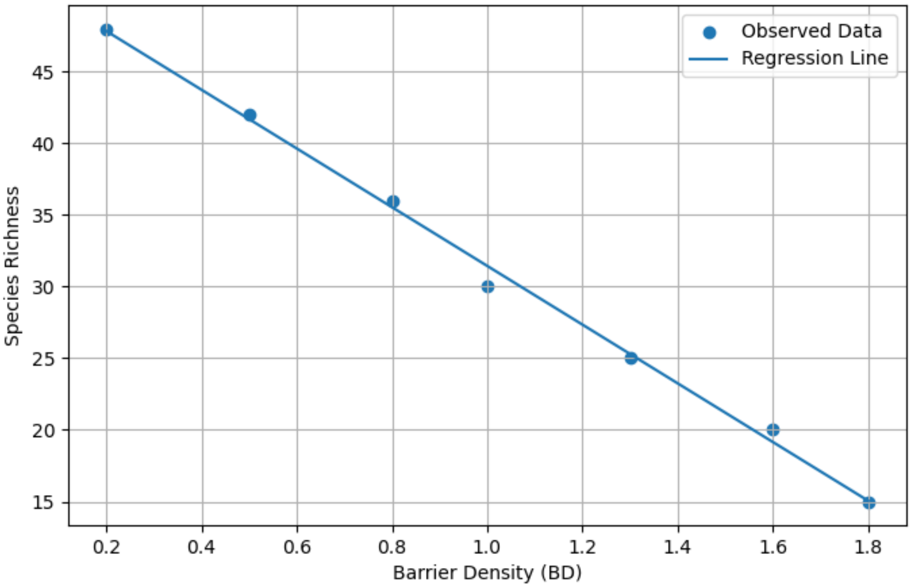

Figure 6: Regression analysis between barrier density and species richness.

Figure 6 gives the regression analysis of barrier density and species richness, which depicts a negative correlation. The relationship is quantitatively supported by a high coefficient of determination ($R^2 \approx 0.92$), indicating a strong inverse association between barrier density and biodiversity. Structural fragmentation has a negative effect on the biodiversity of fish as the barrier density decreases the species richness. Specifically, regions with barrier density exceeding 0.7 dams per 100 km show a reduction in species richness of up to 40%. The regression line indicates how strong and stable this relationship is throughout the area of the study.

Figure 7 shows that there is a positive correlation between Hydrological Connectivity Index (HCI) and species richness. This relationship is quantitatively supported by a strong coefficient of determination ($R^2 = 0.96$), indicating a highly consistent positive association between HCI and biodiversity. The closer the conditions to natural flow regimes, the higher the biodiversity levels as the level of HCI increases. Species richness increases from 15 to 45 across the observed HCI range (0.4 to 0.9), demonstrating a substantial ecological response to improved connectivity. This trend is a focus on the importance of hydrological connectivity in sustaining diverse and healthy fish communities.

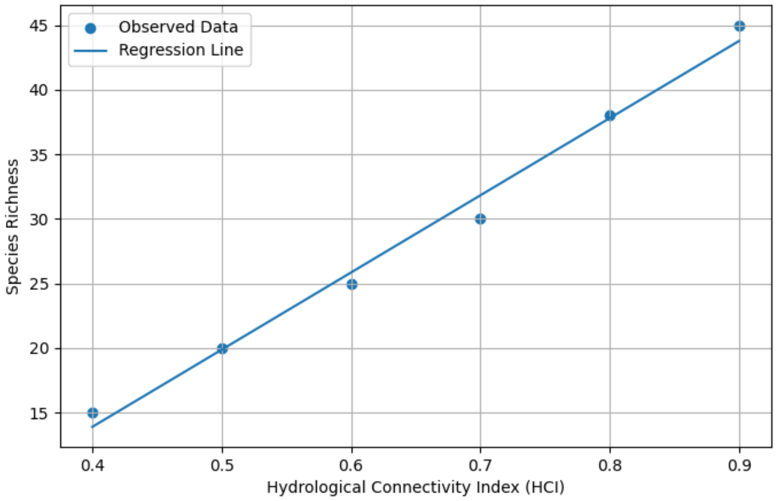

Figure 7: Relationship between hydrological connectivity index and biodiversity.

Discussion

The results emphasize the importance of ecological connectivity in sustaining aquatic life and ecosystems. The data which is more telling as observed in table 3 and figure 5, indicate a steady decline in species richness as the level of connectivity declines. The presence of high connectivity zones facilitates a stable and rich fish community and fragmented habitats has lower species diversity and poor ecological status. Migratory species are being overly affected by physical barriers limiting movement, breeding and feeding grounds, thus causing a decline in population.

The statistical relationships of table 4 further confirm these observations. This is corroborated by the fact that, there is a strong negative relationship between the species richness and barrier density as in figure 6 where aquatic life is greatly disrupted when very fragmented. On the same note, the unfavorable association with fragmentation index is medium implying that there is accumulated ecological stress due to discontinuity in habitat. Quite the contrary, a positive association between hydrological connectivity index and biodiversity is very strong as shown in figure 7 that attests the importance of natural flow regimes and uninterrupted water channels in maintaining the ecological equilibrium.

The fragmentation patterns observed here align with global assessments from recent hydrological datasets. These datasets show that increased dam density is related to decreased ecological connectivity and changes in river ecosystems. This agreement with large-scale studies supports the reliability of these findings and highlights the widespread ecological effects of human-caused river regulation.

Overall, the discussion indicates that hydrological and structural connectivity can be considered as significant predictors of biodiversity dynamics in the freshwater ecosystem. Findings suggest that there is a need to develop sustainable river management programs such as mitigating barriers, restoring and conservation planning of ecological corridors. Connectivity can greatly enhance the resilience of species, restore ecosystem processes and result in environmental sustainability in the long term.

Limitations and Future Work

The paper has conceptualized the approach of assessing the fish habitat connectivity in an elaborate manner; however, it should be noted that it has certain drawbacks. The calculations are done primarily on a simulated data set that is expected to simulate the real-life situation, which may not reflect the complexity and variability of natural ecosystems. Spatial and temporal heterogeneity, seasonal pattern of migration and site-specific environmental factors are explicitly not modeled. The generalized assumptions used in deriving the connectivity indices of the Barrier density (BS), Fragmentation Index (FI) and Hydrological connectivity Index (HCI) could limit the extent to which it could be realistic when used to explain different geographical areas. Another limitation to test the dynamism of the ecosystems is the lack of real-time hydrology monitoring and the ecological monitoring over a long period. The Global Dam Watch dataset might not include smaller or recently built dams, which could result in an undercounting of barrier density and fragmentation. The dataset's temporal updates are also limited, meaning that newly constructed infrastructure might not be immediately included. In addition, the lack of site-specific ecological field validation makes it difficult to fully confirm the modeled biodiversity responses with real-world data.

Overcoming these limitations in future studies is possible through large scale field data, remote sensor data and longitudinal ecological data to enhance the accuracy and generalizability of the model. Complex analytical techniques such as machine learning, geospatial modeling can be used to improve predictive capabilities on biodiversity assessment in varying environmental conditions. Future research should also focus on integrating high-resolution, real-time datasets and incorporating field-based ecological validation to improve the robustness of connectivity assessments. The framework can be further expanded to encompass other ecological indicators like the water quality parameters and species-specific behavioral characteristic to be able to give a more detailed view of the health of an ecosystem. The effects of changes in climates, changes in flows and anthropogenic interventions on the interconnectedness of rivers can be assessed to come up with adaptive and sustainable river management strategies.

Conclusion

This paper gives an in-depth discussion of the connectivity of fish habitat across regulated hydrological systems, which is founded on a multi-layered system. The results clearly give that the importance of connectivity is determinant in ensuring freshwater biodiversity and ecological stability. The statistical analysis showed that the species richness had quite significantly decreased with the change in high connectivity areas (45 species) and low connectivity areas (18 species) which was almost 60 percent reduction. This decline corresponds to connectivity gradients where Hydrological Connectivity Index (HCI) values ranged from 0.9 in near-natural systems to 0.4 in highly regulated sections. The migratory species were especially affected, decreasing to a lower percentage (62 to 19) between networked systems and very fragmented areas respectively indicating the susceptibility of the migratory species to structural hindrances. The strength of these relationships was also highlighted by correlation analysis. It was also found that barrier density was negatively related to species richness ($r = -0.78$, $p < 0.01$) and this confirmed the claim that high fragmentation significantly decreases the biodiversity. Likewise, there was a moderate negative relationship ($r = -0.69$, $p < 0.05$) with the index of fragmentation. On the other hand, there was a positive correlation between the hydrological connectivity index and biodiversity ($r = +0.74$, $p < 0.01$), thus the necessity to maintain the natural flow regimes. Regression analysis further supported these findings with a high coefficient of determination ($R^2 \approx 0.96$), indicating strong predictive relationships between connectivity metrics and ecological responses. Regression analyses, which proved strong directional relationships between measures of connectivity and ecological responses, supported these findings. These observations bring to the fore the importance of having sustainable river management practices, such as the elimination of obstacles, reestablishment of ecological corridors and optimization of flow regimes. To improve on the predictive abilities of the results in the future research, it is suggested that real time monitoring, advanced modeling applications and effects of climatic variability should be included in the research. Future work should also emphasize integration of high-resolution global datasets and field-based ecological validation to enhance model robustness and applicability. The framework could be further enhanced to be more applicable to the entire freshwater conservation process worldwide by expanding the framework to include more ecological indicators, and multi-regional data.

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