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Partial Weir Opening Is Associated with Changes in Diatom Diversity and Ecological Recovery Trajectories in a Monsoonal River

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Highlights

- Partial weir opening caused gradual shifts in diatom assemblages
- Water quality improved after 2021 (↓nutrients, turbidity; ↑DO)
- β-diversity driven by species turnover (~72%)
- Ecological responses were gradual and context-dependent
- Diatoms effectively track hydrological restoration trajectories

Abstract

Partial opening of three weirs (Sejong, Gongju, and Baekje) in the Geum River, South Korea, was implemented in 2020 to partially restore longitudinal flow connectivity. Using seasonal surveys conducted at eight stations from 2020 to 2024, we examined spatiotemporal variation in water quality and benthic diatom assemblages associated with this hydrological intervention. Annual basin-wide averages showed gradual interannual changes in water quality, with declines in total phosphorus, total nitrogen, chlorophyll-a, turbidity, and biochemical oxygen demand after 2021, accompanied by increased dissolved oxygen. Diatom community indices based on relative-abundance data exhibited corresponding temporal variation, with decreased dominance and increased Shannon diversity, evenness, and taxon richness, with significant shifts emerging approximately two years after weir opening. The Bray–Curtis-based Community Dissimilarity Index increased from 0.61 to 0.77 ($p < 0.01$), and β-diversity partitioning indicated that species turnover accounted for 72% of total dissimilarity, suggesting progressive compositional differentiation among sites. Ordination analyses indicated gradual differentiation between assemblages sampled before and after partial weir opening, while random forest models showed limited explanatory power and were treated as exploratory. Indicator species analysis identified period-specific characteristic taxa rather than deterministic species turnover. Overall, partial weir opening was associated with measurable changes in benthic diatom community structure and diversity in a monsoonal river, supporting the use of benthic diatoms as sensitive descriptors for tracking ecological change under flow-regulated conditions.

Keywords: partial weir opening; benthic diatoms; ecological succession; NMDS; random forest; indicator species analysis; river restoration; monsoonal ecosystems

1. Introduction

Weirs and dams, while historically instrumental in supporting water supply, irrigation, and flood control, have been increasingly recognized for their disruptive impacts on riverine ecosystems [1–3]. These structures fragment longitudinal hydrological connectivity, disrupt sediment and nutrient fluxes, and simplify habitat complexity, leading to biodiversity loss and ecological degradation [4–7]. In response, dam removal and weir modification are being implemented globally as strategies to restore ecological integrity and hydromorphological function [8–10].

Ecological responses to hydrological interventions are highly context dependent and vary with climate, flow regime, and biological assemblage composition. In temperate regions, previous studies have documented sediment redistribution, biofilm succession, and biotic recolonization following dam removal or flow restoration [11–13]. In Europe, restoration projects have reported gradual recovery of benthic communities, including macroinvertebrates and periphyton, under re-established flow heterogeneity [14,15]. In contrast, in monsoon-dominated regions such as East Asia, where seasonal hydrological variability is pronounced, empirical evidence on benthic community responses to partial weir opening remains limited, particularly for diatoms [17–19].

Diatoms are widely recognized as effective sentinels of environmental change due to their rapid responses to variation in hydrology, substrate composition, and water chemistry. Their high taxonomic diversity, ecological specificity, and short generation times make them particularly suitable for tracking community-level responses to river restoration and hydrological modification [20–22]. Accordingly, diatom-based indices are commonly used to detect ecological change and community reorganization, rather than to provide direct measures of ecosystem "status" or restoration success. These indices form a core component of several bioassessment frameworks, including the European Water Framework Directive, and are increasingly applied in Asia and North America [23–25].

The Geum River, one of South Korea's major monsoonal rivers, underwent large-scale hydrological alteration during the Four Major Rivers Restoration Project (2009–2011), including the construction of 16 weirs. Subsequent ecological degradation prompted the partial opening of the Sejong, Gongju, and Baekje weirs in 2020 as part of a national river restoration initiative [19,26]. While previous studies have documented changes in water chemistry, phytoplankton dynamics, and fish assemblages following these interventions [27–29], systematic, multi-year assessments of benthic diatom community responses to partial weir opening remain scarce. This gap is particularly evident with respect to spatiotemporal community structure, compositional turnover, and indicator taxa dynamics.

To address this knowledge gap, we conducted a four-year, seasonally resolved biomonitoring program across multiple sites along the Geum River. Specifically, our objectives were to:

(1) quantify spatiotemporal variation in diatom community structure following partial weir opening, without assuming direct causal restoration effects;

(2) examine statistical associations between diatom diversity patterns and environmental variables using multivariate and machine-learning approaches; and

(3) identify period-specific indicator taxa as diagnostic descriptors of assemblage composition, while explicitly avoiding inference of ecological status improvement or deterministic recovery.

2. Materials and Methods

2.1 Study Area and Sampling Design

The Geum River (Geumgang), located in South Korea, extends approximately 400 km from its source in the Sobaek Mountains to its estuary at the Yellow Sea. The river experiences a monsoonal flow regime characterized by pronounced seasonal variability in discharge and turbidity. During the Four Major Rivers Restoration Project (2009–2011), 16 weirs were constructed along the mid- to lower reaches, including the Sejong, Gongju, and Baekje weirs, resulting in substantial hydromorphological and ecological alterations [28,30].

In 2020, partial opening of these three weirs was initiated as part of a national restoration effort aimed at partially reestablishing longitudinal connectivity and improving ecological conditions [19,26]. To assess spatiotemporal ecological responses to this intervention, eight biomonitoring stations were established upstream and downstream of the Sejong, Gongju, and Baekje weirs (Figure

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1). At each station, paired sampling locations were designated on the left (L) and right (R) riverbanks, defined consistently according to flow direction, to account for potential lateral heterogeneity. Seasonal sampling campaigns were conducted twelve times between June 2020 and April 2024, excluding peak monsoon periods to ensure comparability among sampling events. Field surveys followed national river bioassessment protocols [31].

To evaluate whether riverbank position influenced community composition, epilithic diatom samples were initially collected from both banks (L and R). Bank effects were tested using Bray–Curtis dissimilarities and evaluated with PERMANOVA (adonis2) and PERMDISP (betadisper), based on the unit-sum relative-abundance matrix (Table C1, Appendix C) used for all community analyses.

Because no significant bank effect was detected, left and right bank data were pooled for all subsequent analyses. The bank-position test results are summarized together with β-diversity partitioning outputs in Table B1 (Appendix B) (see Section 2.4).

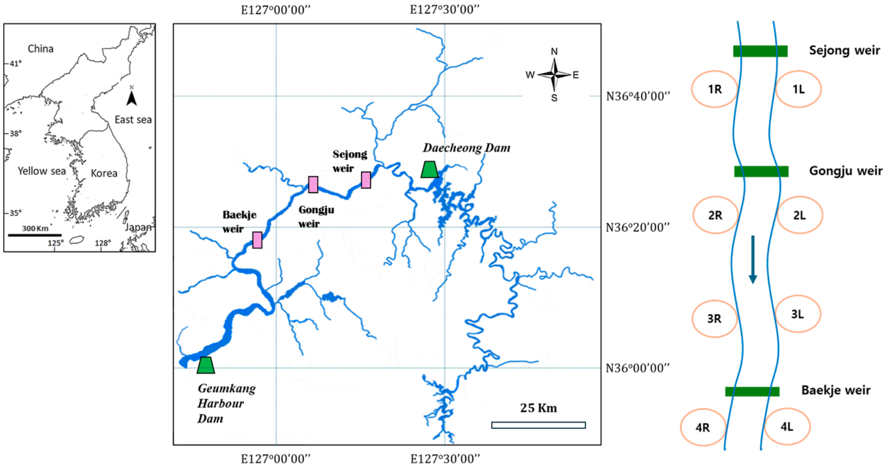

Figure 1. Study area and diatom sampling design in the Geum River (Geumgang), South Korea. The map shows the Geum River basin, including the Daecheong Dam, three weirs (Sejong, Gongju, and Baekje), and the Geumgang Estuary Bank. Eight biomonitoring stations are distributed upstream and downstream of the weirs. At each station, epilithic diatom samples were collected from both the left (L) and right (R) riverbanks, defined according to downstream flow direction, to account for potential lateral heterogeneity.

2.2 Epilithic Diatom Sampling and Identification

Epilithic diatom samples were collected from cobbles in riffles and shallow runs, targeting representative periphytic communities. Biofilms were brushed from a 5 × 5 cm area using sterilized toothbrushes, suspended in distilled water, and preserved with Lugol's iodine. Samples were stored at 4 °C until laboratory analysis. The sampled area was standardized by placing a 5 × 5 cm acrylic template directly onto cobble surfaces during each sampling to ensure consistency across sites and years.

Organic material was oxidized using potassium permanganate ($KMnO_4$) and hydrochloric acid (HCl), and cleaned frustules were mounted on slides with Naphrax®. At least 400 valves per sample were identified to the lowest possible taxonomic level under 1000× magnification, referencing standard floras [32–35]. All diatom taxa were verified against AlgaeBase [36], and valid author citations were provided at the first mention of each species name.

For all comparative and statistical analyses, diatom composition was expressed as relative abundances (%) derived from standardized counts, following established bioassessment practices that emphasize reproducibility and comparability across sites and years. Community attributes were assessed using these relative abundance data to calculate dominance [37], Shannon diversity [38], species richness [39], and Pielou's evenness [40]. All indices were analyzed in their original, non-transformed form. Transformations applied to species abundance matrices for multivariate analyses are described in Section 2.4.

2.3 Water Quality Measurements and Nutrient Analysis

In situ water-quality variables, including temperature (°C), pH, dissolved oxygen (DO, mg L^{-1}), electrical conductivity (EC, µS cm^{-1}), and turbidity (NTU), were measured using a YSI ProDSS multiparameter probe (YSI Inc., USA; accuracy: ±0.1 °C for temperature, ±0.2 mg L^{-1} for DO, and ±1% for EC). Calibration was performed prior to each field campaign following the manufacturer's protocols. Water samples were collected in sterile polyethylene bottles, immediately refrigerated, and transported to the laboratory within 24 h for chemical analyses.

Nutrient concentrations were determined according to standardized methods [31] and corresponding ISO protocols to ensure comparability across sites and sampling periods: nitrate-nitrogen (NO_3^--N; ISO 7890-3:1988), ammonium-nitrogen (NH_4^+-N; ISO 7150-1:1984), total nitrogen (TN; ISO 11905-1:1997), orthophosphate-phosphorus (PO_4^{3-}-P; ISO 6878:2004), and total phosphorus (TP; ISO 15681-2:2003). Biochemical oxygen demand (BOD_5) was determined using the dilution method (ISO 5815-1:2003). Chlorophyll-a (Chl-a) was measured spectrophotometrically (Hitachi U-2900, Japan) following acetone extraction, with an analytical precision of ±0.5 µg L^{-1}. All analyses were performed in triplicate for quality control.

To facilitate comparison with diatom assemblage metrics based on relative abundances, nutrient and water-quality variables were treated as standardized continuous predictors in multivariate analyses (Section 2.4). For visualization in Figure 2, annual mean values across the eight monitoring sites were averaged to illustrate basin-wide trends. Each parameter was normalized within its annual range (0–1) to emphasize relative interannual variability rather than absolute magnitudes. Detailed site-level spatiotemporal variability is presented in Figure F1 (Appendix F).

2.4 Statistical Analyses and Ecological Modeling

All statistical analyses were conducted in R (v4.3.1) [41] and PAST (v4.11) [42]. All community-level analyses were based exclusively on relative-abundance data; absolute density values were not used in any statistical tests.

- *Data preprocessing:* Raw diatom valve counts were standardized on a per-sample basis to generate a unit-sum relative-abundance matrix, in which the relative abundances of taxa within each sample sum to 1.0. This matrix (Table C1, Appendix C) served as the sole input for all community-level analyses, ensuring comparability among samples and consistency with the assumptions of distance-based and diversity analyses.
- *Transformations:* Transformations were applied only when required by the analytical framework. For ordination methods based on Euclidean geometry (PCA and distance-based redundancy analysis, dbRDA), the relative-abundance matrix was Hellinger-transformed [43]. Bray–Curtis–based analyses (NMDS, β-diversity partitioning, PERMANOVA, PERMDISP, and indicator species analysis) were conducted on non-transformed relative-abundance data. Diversity indices (Shannon diversity, richness, evenness, and dominance) were calculated exclusively from non-transformed relative abundances. Log(x + 1) transformation was used only for visualization purposes and was not used as input for statistical tests.
- *Univariate analyses:* Differences in Shannon diversity (H′), richness, evenness, and dominance between pre-opening (2020–2021) and post-opening (2022–2024) periods were tested after assessing normality [44]. Paired t-tests were applied when assumptions were met; otherwise, Wilcoxon signed-rank tests were used [45]. Effect sizes (Cohen's d or r) were reported alongside p-values, and false discovery rate (FDR) correction [46] was applied to account for multiple comparisons.
- *Multivariate ordination:* Non-metric multidimensional scaling (NMDS) based on Bray–Curtis dissimilarities was used to summarize community patterns; stress values around 0.3 were interpreted as indicating moderate fit. Principal component analysis (PCA) was applied to Hellinger-

transformed species data and standardized environmental variables to identify major gradients. Environmental vectors were fitted using envfit() to aid interpretation. Distance-based redundancy analysis (dbRDA) was used to constrain assemblage composition by environmental variables; results are presented in Figure F3 (Appendix F).

- *β-diversity and community diagnostics:* β-diversity was partitioned into turnover and nestedness components using the betapart package [47], quantifying the relative contributions of species replacement and nested species loss/gain. Group differences were evaluated using PERMANOVA and PERMDISP [48,49]. SIMPER analysis was used to identify taxa contributing most to dissimilarities between groups [50]. Site-level mean Bray–Curtis dissimilarities were correlated with local Shannon diversity (H′).
- *Indicator species analysis (ISA):* Indicator species analysis was conducted using the indicspecies package [51] with 999 permutations to identify taxa significantly associated with each temporal group.
- *Random forest (RF) and generalized additive models (GAMs):* Random forest regression (500 trees) was used to explore potential environmental predictors of Shannon diversity. Variable importance was assessed using permutation-based changes in R^2, and partial dependence plots were used to visualize non-linear relationships. Generalized additive models (GAMs) with cubic regression splines (mgcv package) [52] were used to capture non-linear temporal trends in diversity indices.

3. Results

3.1 Spatiotemporal Trends in Water Quality and Diatom Community Indices

Annual basin-wide means of water-quality parameters exhibited clear interannual variation across the eight monitoring sites during the study period (2020–2024) (Figure 2; Figures F1 and F2 in Appendix F). Total phosphorus (TP), total nitrogen (TN), and chlorophyll-a concentrations declined after 2021, while biochemical oxygen demand (BOD_5) and turbidity (NTU) also decreased. Dissolved oxygen (DO) increased over the same period, whereas electrical conductivity (EC) showed moderate interannual fluctuations.

Benthic diatom community indices calculated from relative-abundance data also varied among years (Figure 3). Mean dominance values decreased after 2021, whereas Shannon diversity (H′), Pielou’s evenness (J′), and Margalef richness (e′) showed higher mean values in 2022–2024 compared with 2020–2021. Interannual variability of all indices is summarized as mean ± SD, and no ecological interpretation is included at this stage (Figure 3).

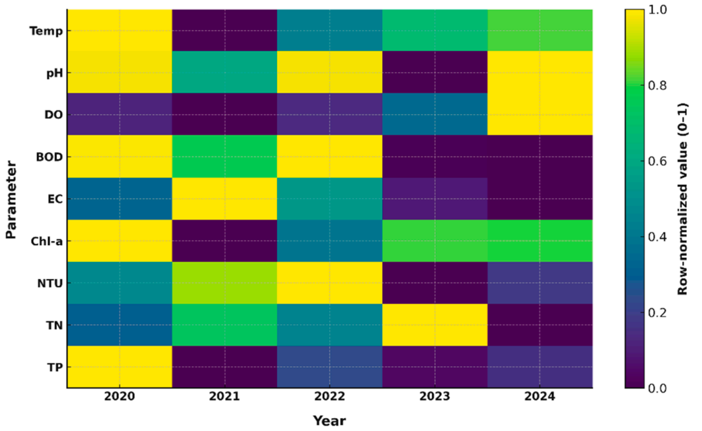

Figure 2. Annual basin-wide mean values of nine water-quality parameters (2020–2024) across eight monitoring sites. Parameters include temperature, pH, dissolved oxygen (DO), biochemical oxygen demand (BOD_5), electrical conductivity (EC), chlorophyll-a (Chl-a), turbidity (NTU), total nitrogen (TN), and total phosphorus (TP). Values were normalized (0–1) within each parameter to visualize relative interannual variability.

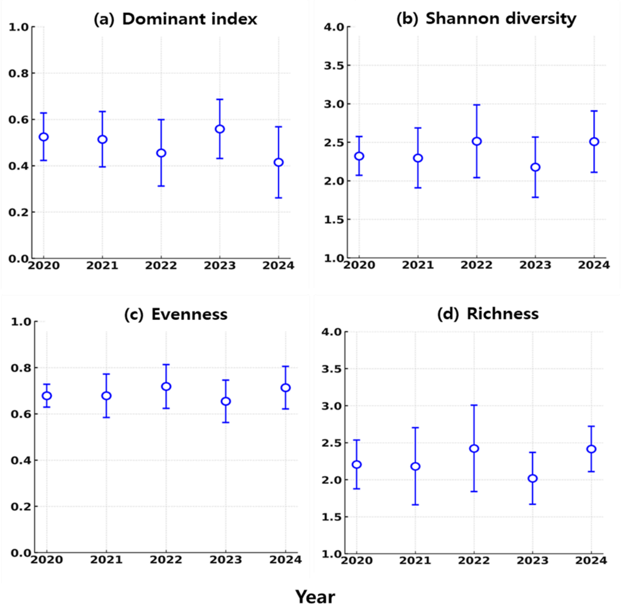

Figure 3. Annual trends in benthic diatom community indices (2020–2024) across eight monitoring sites. Mean ± SD values are shown for dominance, Shannon diversity (H′), Pielou’s evenness (J′), and Margalef richness (e′), calculated from unit-sum relative-abundance data.

3.2 Temporal Dynamics of Diatom Diversity and Community Dissimilarity

Mean Community Dissimilarity Index (CDI) values increased from 0.61 (2020) to 0.77 (2024), with the largest increase occurring between 2021 and 2022 (Figure 4). CDI values during 2022–2024 were higher than those during 2020–2021 (Wilcoxon signed-rank test, $p < 0.01$). Mean Shannon diversity (H′) also varied among years, with higher values observed in 2022 and 2024 (Figure 4).

β-diversity partitioning based on the Baselga framework [47] indicated that species turnover accounted for 72% of total dissimilarity, whereas nestedness accounted for 28% (Table B1, Appendix B). These values summarize the relative contributions of turnover and nestedness to compositional variation across the study period.

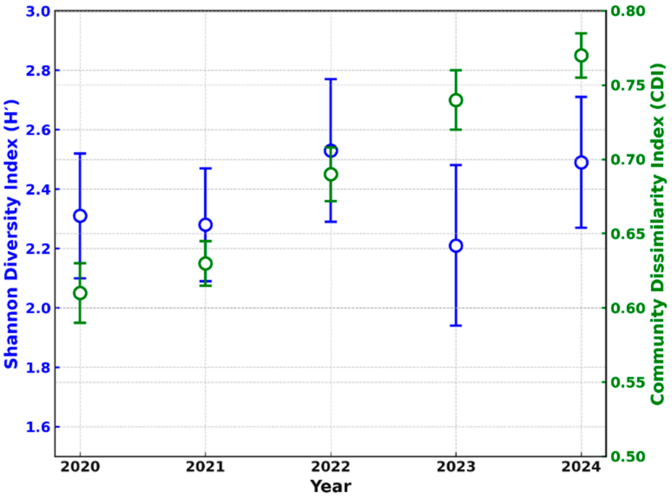

Figure 4. Annual variation in Shannon diversity (H′) and Community Dissimilarity Index (CDI) from 2020 to 2024. Values represent mean ± SD calculated from unit-sum relative-abundance matrices. CDI reflects Bray–Curtis–based compositional dissimilarity among sites.

3.3 Ordination Analysis and Environmental Gradients

Non-metric multidimensional scaling (NMDS) based on Bray–Curtis dissimilarities showed partial separation between assemblages sampled during 2020–2021 and those sampled during 2022–2024 in ordination space (Figure 5a). The NMDS solution had a stress value of 0.32. Assemblages from 2022–2024 occupied a broader ordination space, consistent with greater dispersion in later years.

Principal component analysis (PCA) of environmental variables indicated that the first two axes explained 26.2% (PC1) and 23.3% (PC2) of total variance, respectively (Figure 5b). Nutrient- and turbidity-related variables (TP, TN, chlorophyll-a, NTU) exhibited high loadings along the major gradients. Distance-based redundancy analysis (dbRDA) yielded comparable gradient structures (Figure F3 in Appendix F).

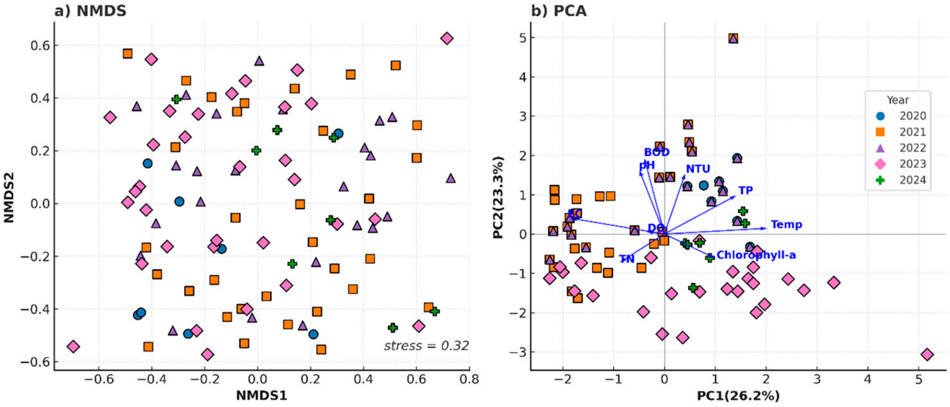

Figure 5. Ordination of diatom assemblages and environmental variables across the study period. (a) NMDS ordination based on Bray–Curtis dissimilarities (stress = 0.32). (b) PCA biplot of environmental variables, with PC1 and PC2 explaining 26.2% and 23.3% of total variance, respectively.

3.4. Environmental Predictors of Diatom Diversity

Random forest regression explained a limited proportion of the variance in Shannon diversity (out-of-bag $R^2 = -0.03$; RMSE = 0.42; Figure 6). Permutation-based variable importance ranked chlorophyll-a, dissolved oxygen, biochemical oxygen demand, and pH as relatively higher-importance predictors, whereas total nitrogen and turbidity showed lower importance.

Partial dependence analysis indicated a weak, non-linear relationship between chlorophyll-a concentration and predicted Shannon diversity, with higher predicted values at intermediate concentrations (Figure 6b).

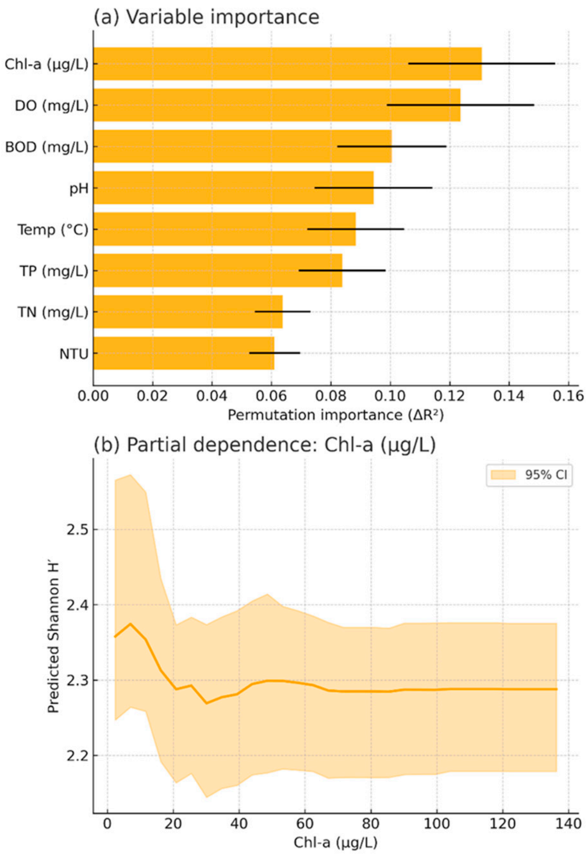

Figure 6. Random forest analysis of environmental predictors of Shannon diversity (H′). (a) Permutation-based variable importance (mean ± 95% CI). (b) Partial dependence of predicted H′ on chlorophyll-a concentration.

3.5. Indicator Taxa Associated with Pre- and Post-Opening Periods

Indicator species analysis (ISA; 999 permutations) identified five taxa with indicator values > 0.6 ($p < 0.01$). Navicula gregaria, Stephanodiscus hantzschii, and Achnanthidium gracillimum were associated with the 2020–2021 period, whereas Pseudostaurosira elliptica and Cyclotella choctawhatcheeana were associated with the 2022–2024 period.

Mean relative abundances (± SD) of these taxa differed between the two periods, and the corresponding indicator values are shown in Figure 7.

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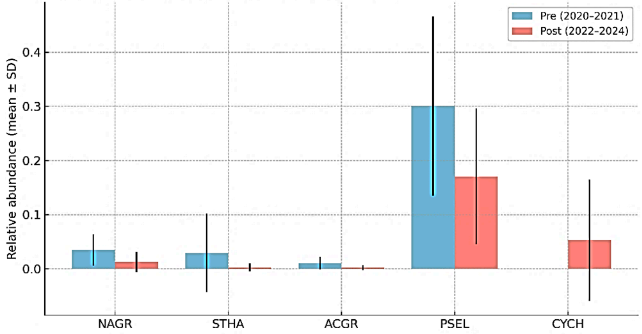
(a) Indicator taxa abundances (pre vs post)



(b) Indicator values (ISA)

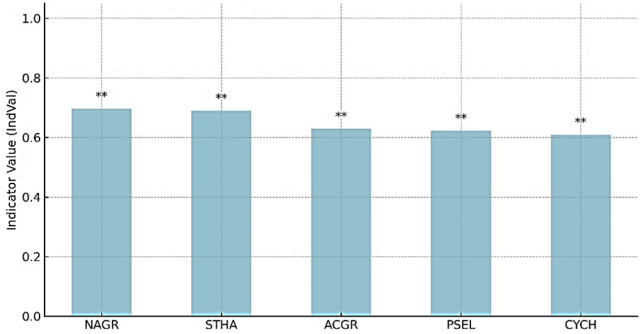


Figure 7. Indicator taxa distinguishing assemblages sampled during 2020–2021 and 2022–2024. (a) Mean (± SD) relative abundances of indicator taxa. (b) Indicator values (IndVal) with significance levels (* $p < 0.05$, ** $p < 0.01$).

4. Discussion

4.1 Hydrological Restoration and Ecological Responses

Following partial weir opening, benthic diatom assemblages exhibited gradual and measurable changes in community structure rather than abrupt shifts. Diversity-related indices, including Shannon diversity, richness, and evenness, tended to increase during the post-opening period, whereas dominance declined. These temporal patterns coincided with partial restoration of flow connectivity; however, they do not imply direct causality. Instead, the observed responses are more appropriately interpreted as progressive community reorganization rather than immediate or complete ecological recovery, thereby avoiding overstatement of system resilience.

Similar associations between enhanced hydraulic variability and benthic community responses have been reported in other river restoration studies, where increased flow heterogeneity and substrate diversity were linked to gradual changes in periphytic and macroinvertebrate assemblages [9,14,56]. Comparable patterns have also been documented in Korean rivers influenced by weir regulation and subsequent flow modification [19,57]. Collectively, these studies indicate that hydrological interventions are often associated with slow, multi-year ecological adjustment rather than rapid system-wide recovery. The magnitude and timing of responses are known to depend strongly on local flow regimes, geomorphic context, and disturbance history [55,56].

4.2 Global Context of Diatom Diversity Recovery

The temporal trajectories observed in this study align broadly with international river restoration literature while highlighting region-specific dynamics. In temperate river systems, benthic assemblages commonly show slow recovery trajectories following hydrological restoration, often extending over several years [14,58]. In contrast, monsoon-dominated rivers such as the Geum River experience pronounced seasonal hydrological pulses that can drive relatively rapid short-term compositional shifts, favoring disturbance-tolerant or pioneer diatom taxa [19,26,57].

These contrasts suggest that while general restoration principles may be shared across regions, the pace and direction of community change are strongly modulated by climatic and hydrological regimes. This underscores the importance of regionally calibrated assessment frameworks that explicitly account for hydrological variability and disturbance intensity [58–60]. Diatom-based indices remain useful for tracking temporal ecological change, but direct cross-regional comparisons should be approached cautiously due to differences in species pools, disturbance regimes, and environmental context [21,24].

4.3 Environmental Drivers of Diatom Diversity

Random forest analyses identified chlorophyll-a, dissolved oxygen, biochemical oxygen demand, and pH as relatively influential variables; however, the very low explanatory power of the models indicates that these relationships are exploratory rather than predictive. Accordingly, RF results are interpreted as descriptive associations rather than evidence of environmental control over diatom diversity.

The weak, non-linear association between chlorophyll-a concentration and Shannon diversity—characterized by higher diversity at intermediate concentrations—resembles patterns often discussed in the context of the intermediate disturbance hypothesis. However, this similarity should not be interpreted as mechanistic support for that hypothesis in the present system [62,63]. In flow-regulated rivers, hydrological variability, substrate heterogeneity, and disturbance frequency are likely to exert stronger influence on benthic diatom assemblages than water-quality variables alone [64–66].

Future modeling efforts would benefit from integrating physical habitat descriptors, hydrological metrics, and biological trait information to better characterize drivers of community dynamics and recovery trajectories following hydrological interventions [67–69].

4.4 Indicator Taxa and Ecological Trajectories

Indicator species analysis identified taxa that were statistically associated with pre- and post-opening periods, serving as diagnostic descriptors of assemblage composition rather than quantitative measures of species turnover. Pre-opening assemblages were characterized by Navicula gregaria, Stephanodiscus hantzschii, and Achnanthidium gracillimum, whereas post-opening assemblages were associated with Pseudostaurosira elliptica and Cyclotella choctawhatcheeana.

These temporal shifts in characteristic taxa coincided with changes in hydrological and nutrient conditions; however, they do not constitute direct evidence of deterministic species replacement or improved ecological status. Similar transitions from eutrophic or low-flow–associated taxa toward more flow-associated diatoms have been reported in Korean rivers [19,57] as well as in European restoration contexts [14,70].

Such compositional reorganization is most appropriately interpreted as gradual ecological realignment under modified flow conditions, consistent with early-stage recovery processes, rather than as confirmation of enhanced resilience or ecosystem stabilization [71–73]. Despite these limitations, benthic diatoms remain sensitive indicators of ecological change following hydrological interventions [21].

4.5 Methodological Considerations and Limitations

Several methodological limitations should be acknowledged. First, the limited explanatory power of RF models highlights the need to incorporate hydrological and habitat-scale variables alongside water-quality metrics in future analyses [56,76]. Second, indicator taxa identified in this study likely exhibit regional specificity, limiting direct transferability to other river systems [24].

Third, exclusion of peak monsoon periods—implemented to minimize flood-related sampling constraints—may have reduced sensitivity to short-term disturbance and recovery dynamics characteristic of monsoonal rivers [57,77]. Finally, taxonomic diversity indices alone cannot fully capture functional, productivity-related, or ecosystem-level responses. Future restoration assessments would benefit from multi-metric approaches integrating functional traits, molecular tools, and ecosystem process indicators [68,75,77].

5. Conclusion

This study shows that partial weir opening was temporally associated with measurable changes in benthic diatom diversity and community composition, expressed as gradual shifts in assemblage structure over multiple years. Using multivariate ordination, random forest analysis, and indicator species analysis, we identified statistically supported patterns of community variation that coincided with partial hydrological reconnection, without implying direct causal restoration effects.

Shannon diversity increased by approximately 25%, dominance declined by ~32%, and taxon richness increased by ~33% during the post-opening period based on unit-sum relative-abundance data. These changes reflect progressive community reorganization following hydrological intervention rather than complete ecological recovery or enhanced resilience. The observed trajectories suggest that even partial restoration of longitudinal connectivity may facilitate gradual ecological adjustment in flow-regulated rivers, particularly where full dam removal is not feasible.

From a management perspective, benthic diatom assemblages provide a sensitive and cost-effective means of tracking ecological change when interpreted as descriptors of community structure rather than direct measures of ecological status. However, limitations include exclusion of peak monsoon periods, reliance on taxonomic and relative-abundance metrics, and the limited explanatory power of water-quality–based models.

Future restoration assessments would benefit from integrating hydrological metrics, habitat-scale descriptors, functional or trait-based indicators, and emerging molecular approaches. Overall, this study provides empirical evidence that partial weir opening can be associated with measurable ecological change in monsoonal rivers, while underscoring the need for cautious interpretation and regionally calibrated, long-term monitoring frameworks.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

Author Contributions: Conceptualization, Y.J.K. and B.-H.K.; Methodology, S.-O.H. and B.-H.H.; Software, S.-O.H.; Formal analysis, S.-O.H., B.-H.H., Y.J.K., and B.-H.K.; Investigation, Y.J.K. and B.-H.K.; Data curation, S.-O.H., B.-H.H., Y.J.K., and B.-H.K.; Writing—original draft preparation, S.-O.H.; Writing—review and editing, Y.J.K. and B.-H.K.; Supervision, B.-H.K.; Project administration, Y.J.K. and B.-H.K. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement : All community-level analyses in this study were conducted using a unit-sum relative-abundance (RA) matrix ($\Sigma p = 1.0$ per sample). The final analytical species-by-sample relative-abundance matrix is provided as Table C1 (Appendix C). Results of β-diversity partitioning and multivariate diagnostics (including PERMANOVA, PERMDISP, and SIMPER) are provided in Table B1 (Appendix B). Additional metadata describing the sampling design and temporal classification are provided in Table D1 (Appendix D), and spatial characteristics of sampling sites are provided in Table E1 (Appendix E). Supplementary visual materials, including site-level heatmaps and ordination results, are presented in Figures F1–F3 (Appendix F), which complement the basin-scale summaries in the main text. All statistical analyses were conducted using R, and the complete analytical workflow is described in the Materials and Methods section. R scripts used for data preprocessing and statistical analyses are available from the corresponding author upon reasonable request.

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

Abbreviations

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The following abbreviations are used in this manuscript:

BD	Benthic Diatoms
RA matrix	Unit-sum Relative-Abundance matrix ($\Sigma p = 1.0$)
CDI	Community Dissimilarity Index (Bray–Curtis-based)
β-div	Beta diversity
β_turn	Species replacement component of β-diversity (Turnover)
β_nest	Species loss/gain component of β-diversity (Nestedness)
NMDS	Non-metric Multidimensional Scaling
PCA	Principal Component Analysis
dbRDA	Distance-based Redundancy Analysis
PERMANOVA	Permutational Multivariate Analysis of Variance
PERMDISP	Permutational Analysis of Multivariate Dispersion
SIMPER	Similarity Percentage Analysis
ISA	Indicator Species Analysis
RF	Random Forest
H′	Shannon Diversity Index
J′	Pielou’s Evenness
e′	Margalef Richness
D	Dominance Index
TP	Total Phosphorus
TN	Total Nitrogen
Chl-a	Chlorophyll-a
BOD_5	Biochemical Oxygen Demand (5-day)
DO	Dissolved Oxygen
EC	Electrical Conductivity
NTU	Turbidity
Pre-O	Pre-opening period (2020–2021)
Post-O	Post-opening period (2022–2024)

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