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Monsoon-driven community assembly and diversity structure of aquatic insects in the Chaliyar River, Western Ghats, India

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Abstract
Aquatic insects are key bioindicators of freshwater ecosystem health, yet their dynamics in tropical monsoon-fed rivers remain poorly understood. This study investigated spatio-temporal variation in aquatic insect assemblages in the Chaliyar River, Kerala, India, across seven sites during pre-monsoon, monsoon, and post-monsoon seasons of 2023. A total of 994 individuals representing 29 families and six orders were recorded, with Odonata dominating the assemblage (37.42%), particularly Gomphidae. Significant seasonal differences were observed in abundance (H = 15.52, p < 0.001) and community composition (χ^2 = 477.13, p < 0.001). Abundance was lowest during the monsoon (n = 211), likely due to hydrological disturbance, whereas taxonomic richness peaked during this period (Margalef H = 7.56, *p* = 0.023). Beta diversity analysis indicated that seasonal variation was primarily driven by taxonomic turnover rather than nestedness. These results highlight the role of monsoon-driven hydrological dynamics in shaping community structure and maintaining biodiversity in tropical river ecosystems. This underscores the necessity of considering seasonal flow regimes when evaluating the ecological integrity of such systems.

Keywords: Freshwater ecology, Community assembly, Alpha diversity, Beta diversity, Western Ghats

Introduction

Freshwater ecosystems occupy less than 1% of the Earth's surface yet support nearly 10% of known animal species, with aquatic insects forming a major component of biodiversity. Approximately 45,000 insect species inhabit freshwater habitats globally, including around 5,000 species reported from inland wetlands of India (Harinagaraj *et al*., 2024) [10]. Owing to their diverse functional traits and varying sensitivities to environmental perturbations, aquatic insects are widely recognized as valuable bioindicators of water quality and ecosystem health (Athulya *et al*., 2024) [3]. Belonging to orders such as Ephemeroptera, Odonata, Plecoptera, Trichoptera, Diptera, Coleoptera, and Hemiptera, they play essential roles in aquatic food webs, nutrient cycling, and ecosystem functioning (Wallace & Webster, 1996) [29].

Aquatic insects are extensively used in freshwater biomonitoring because their responses to environmental stress closely reflect ecological conditions. Sensitive taxa decline under degraded conditions, whereas pollution-tolerant groups persist, making community composition a reliable indicator of freshwater ecosystem health (Mahmoud & Riad, 2020) [16]. Anthropogenic disturbances, including sewage discharge, agricultural runoff, and habitat modification, alter physicochemical characteristics such as dissolved oxygen, temperature, and nutrient concentrations, thereby influencing the diversity, abundance, and distribution of aquatic insect assemblages (Tabassum *et al*., 2024) [28].

Tropical monsoon-fed rivers are characterized by pronounced seasonal fluctuations in stream discharge, sediment transport, and habitat availability, all of which strongly influence aquatic macroinvertebrate communities. Seasonal hydrological variability affects not only local species richness (alpha diversity) but also community turnover (beta diversity) through habitat filtering, dispersal, and taxonomic replacement (Baselga, 2010) [5]. Although several studies have documented aquatic insect diversity in Indian rivers, most have focused on species inventories or water quality assessment, with comparatively limited attention given to seasonal community assembly and beta diversity, particularly in the monsoon-driven rivers of the Western Ghats. Consequently, the ecological mechanisms underlying seasonal changes in aquatic insect assemblages remain insufficiently understood, limiting the development of robust biomonitoring and conservation strategies for these ecologically significant river systems.

Biodiversity indices such as the Shannon–Wiener and Simpson indices, together with beta diversity metrics and multivariate community analyses, provide valuable insights into community structure, seasonal turnover, and ecological integrity of freshwater ecosystems (Liu *et al*., 2025) [15]. Against this background, the present study investigated the spatio-temporal variation, diversity patterns, and community assembly of aquatic insects across selected stations of the Chaliyar River, Kerala, India. Specifically, the objectives were to (i) characterize seasonal changes in aquatic insect community composition, (ii) evaluate alpha and beta diversity patterns across sampling sites and seasons, and (iii) assess the influence of monsoon-driven hydrological variation on aquatic insect assemblages.

Materials and Methods

1. Study Area

Seven sampling stations were selected along the Chaliyar River and its tributaries, including three tributary sites and four main channel locations (Fig 1). The stations were selected to represent variations in environmental conditions and anthropogenic disturbances along the river basin. The sampling sites include Kottappuzha (T1:11.240981°N, 76.311765°E), Kuthirappuzha (T2: 11.264520° N, 76.238914°E), Kuruvanpuzha (T3: 11.311773°N, 76.199337°E), Nilambur (S1: 11.282929°N, 76.228793°E), Mampad (S2: 11.250984°N, 76.180354°E), Edavanna (S3: 11.219721°N, 76.140495°E) and Areekode (S4: 11.222924°N, 76.060039°E). These stations represent a gradient from relatively undisturbed upstream regions to downstream areas experiencing higher anthropogenic pressure.

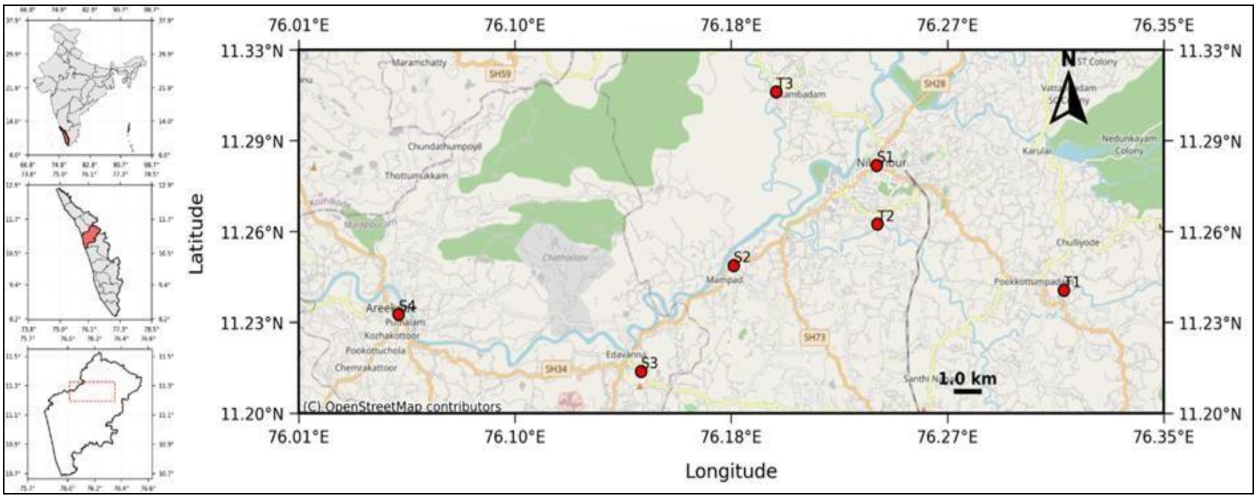


Fig 1: Location map of the sites representing three tributary (T1-T3) sites and four main stream sites (S1-S4).

Sampling and Identification of Aquatic Insects

Aquatic insects were sampled from selected stations of the Chaliyar River during pre-monsoon, monsoon, and post-monsoon seasons of 2023 to assess seasonal variation in community structure. Sampling was conducted using standard benthic techniques, including kick sampling and dip-netting, following established freshwater biomonitoring protocols (Saha *et al.*, 2017) [23]. Collections were made from diverse microhabitats such as marginal vegetation, submerged substrates, and flowing sections to ensure representative coverage. Substrates were manually disturbed while nets were positioned downstream to collect dislodged organisms, and surface-dwelling insects were collected by net sweeping and hand-picking.

Specimens were preserved in 70% ethanol and transported to the laboratory for identification. Aquatic insects were sorted and identified to the family level using morphological characteristics under a stereo zoom microscope, following standard taxonomic keys (Subramanian and Sivaramakrishnan, 2007) [27]. Abundance data were recorded for each family across sampling sites and seasons.

Statistical Analysis

Statistical analyses were performed in R (R Core Team, 2023) to evaluate spatio-temporal variation in aquatic insect diversity. Normality and homogeneity of variance were assessed using the Shapiro–Wilk test and Levene's test, respectively. Alpha diversity was estimated using the Shannon–Wiener index (H′), Simpson's index (1–D), Chao-1, Margalef's richness, and Pielou's evenness, along with the relative abundance (%) of families. Seasonal differences in diversity indices were tested using the Kruskal–Wallis test, followed by Dunn's post hoc test with Bonferroni correction where applicable.

Community composition was analysed using hierarchical clustering, heatmaps, and Bray–Curtis-based NMDS and PCoA ordinations. Community similarity was evaluated using Sørensen, Jaccard, and Bray–Curtis indices, whereas beta diversity was partitioned into turnover, nestedness, balanced variation, and abundance-gradient components. Seasonal and spatial differences in community composition were tested using PERMANOVA (Anderson, 2001) [1]. Rényi diversity, Hill diversity, and rank–abundance distribution analyses were also performed. Graphical outputs, including bar charts, heatmaps, diversity profiles, ordination plots, and dendrograms, were used to visualise community patterns.

Result

1. **Community Composition and Seasonal Variation of Aquatic Insect Assemblages**

A total of 994 aquatic insect individuals representing 29 families and six orders were recorded from the Chaliyar River (Table 1). The assemblage was strongly dominated by Odonata, with Gomphidae as the most abundant family (37.42%), followed by Corduliidae (15.79%) and Cordulegastridae (11.67%). Hemiptera and Coleoptera were moderately represented, particularly by Nepidae and Dytiscidae, whereas sensitive groups such as Ephemeroptera and Plecoptera were recorded in low abundance.

Seasonal variation strongly influenced community structure. The post-monsoon (395 individuals) and pre-monsoon (388 individuals) seasons showed the highest abundances, while the monsoon recorded the lowest abundance (211 individuals). Despite reduced abundance during the monsoon, taxonomic richness was higher. Spatial heterogeneity further contributed to variation in community structure, with certain sites exhibiting higher richness. The post-monsoon period reflected recovery and recolonization of aquatic insect communities following monsoon disturbance.

Table 1: Seasonal composition, abundance, and relative dominance of aquatic insect families recorded from the Chaliyar River during the study period.

Order	Family	Pre-M	Mon	Post-M	total	MEAN± SD	Relative abundance (%)
Odonata	Gomphidae	98	82	192	372	124±59.43	37.42
	Macromiidae	36	13	22	71	23.67±11.6	7.14
	Libellulidae	14	4	14	32	10.67±5.77	3.22
	Cordulegastridae	68	1	47	116	38.67±34.26	11.67
	Corduliidae	82	20	55	157	52.33±31.1	15.79
	Coenagrionidae	14	7	8	29	9.67±3.79	2.92
	Platystictidae	1			1	1	0.1
	Platycnemididae	1			1	1	0.1
	Lestidae	4			4	4	0.4
	Aeshnidae	25	2		27	13.5±16.3	2.72
	Calopterygidae	14			14	14	1.41
	Chlorocyphidae	2	2	4	8	2.67±1.15	0.81
Hemiptera	Nepidae	7	9	8	24	8	2.41
	Naucoridae	14		5	19	9.5±6.36	1.91
	Belostomatidae		1		1	1	0.1
	Gerridae		21		21	21	2.11
	Hydrometridae		1		1	1	0.1
	Pleidae		4		4	4	0.4
Coleoptera	Dytiscidae	4	9	31	44	14.67±14.36	4.43
	Noteridae		12	7	19	9.5±3.5	1.91
	Gyrinidae		12		12	12	1.21
Ephemeroptera	Baetidae		1		1	1	0.1
	Caenidae		2		2	2	0.2
	Leptophlebiidae	1	1		2	1	0.2
	Heptageniidae	3	2		5	2.5±0.7	0.5
Lepidoptera	Pyralidae		1		1	1	0.1
Orthoptera	Tetrigidae		3		3	3	0.3
Plecoptera	Perlidae		1		1	1	0.1
Hymenoptera	Ichneumonidae			2	2	2	0.2
		388	211	395	994		

Stacked Bar Chart Showing Relative Abundance of Aquatic Insect Families

The relative abundance of aquatic insect families varied across sampling sites and seasons (Fig 2). Gomphidae was the dominant family at most sites, while the proportional contributions of other families, including Corduliidae, Coenagrionidae, Chlorocyphidae, Gerridae, and Dytiscidae, differed among locations. Several families were restricted to specific sites or occurred at low relative abundances, indicating spatial heterogeneity in community composition.

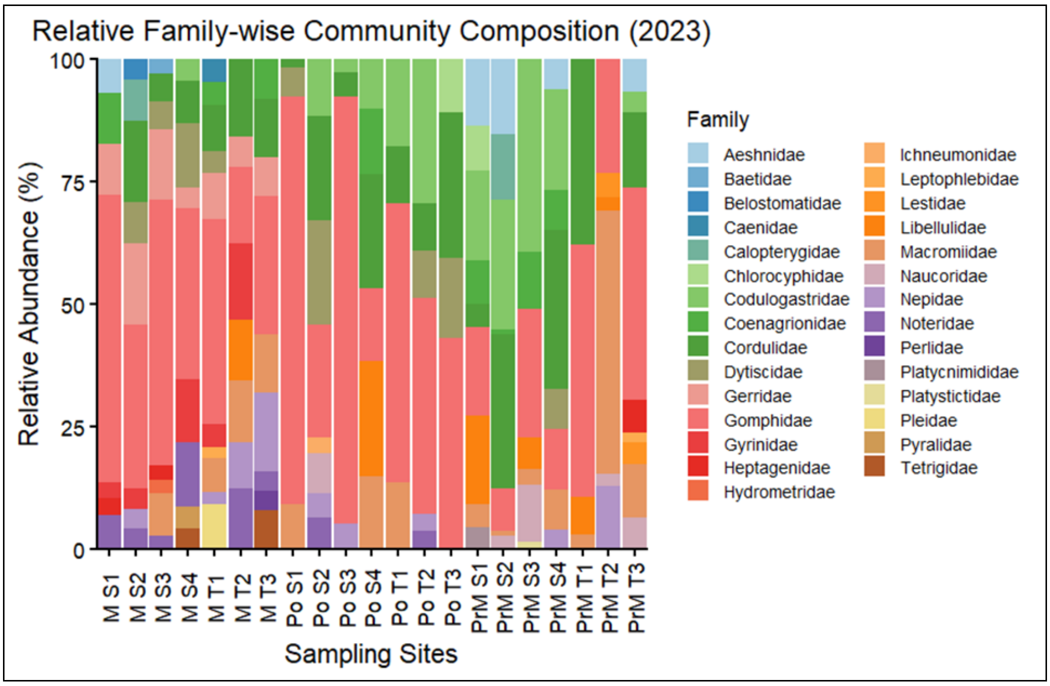


Fig 2: Relative abundance (%) of aquatic insect families recorded at sampling sites during pre-monsoon (PrM), monsoon (M), and post-monsoon (Po) seasons in the Chaliyar River. Each stacked bar represents the proportional contribution of each family to the total assemblage at a sampling site.

Hierarchical Clustering and Family-wise Community Structure of Aquatic Insects

The hierarchical clustering heatmap revealed spatial variation in the family-level composition of aquatic insect assemblages across sampling sites (Fig 3). Families such as Gerridae, Coenagrionidae, Corduliidae, and Dytiscidae were distributed across multiple sites, whereas Hydrometridae, Belostomatidae, and Chlorocyphidae showed more localized occurrence. Hierarchical clustering grouped sampling sites with similar assemblage composition, while distinct clusters reflected differences in family distribution among sites. Variations in standardized abundance values further highlighted spatial heterogeneity in community structure.

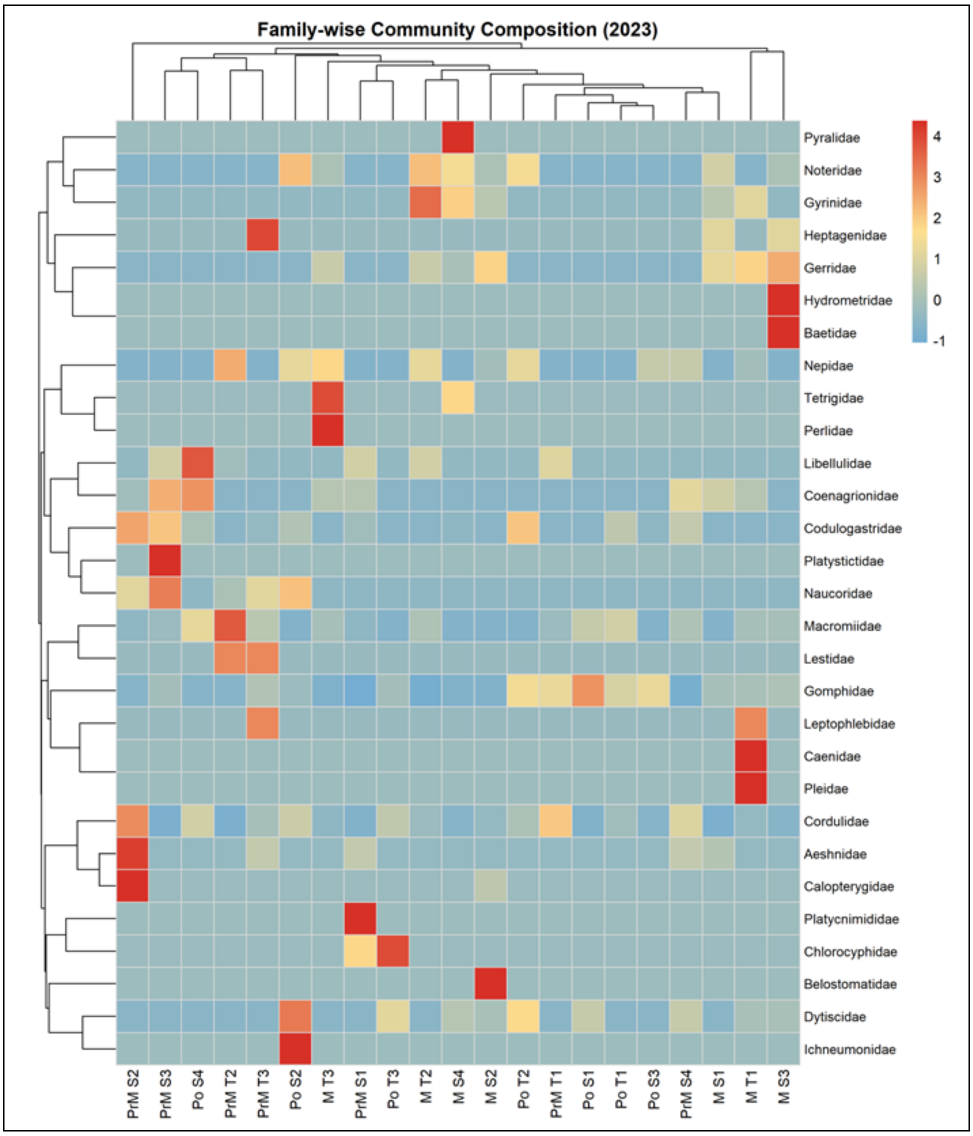


Fig 3: Heatmap showing the standardized abundance of aquatic insect families across sampling sites and seasons in the Chaliyar River. Colour gradients represent standardized abundance values, with warmer colours indicating higher abundance. Dendrograms illustrate hierarchical clustering of aquatic insect families and sampling sites based on Euclidean distance.

Seasonal Variation in Community Composition

A chi-square test revealed significant seasonal differences in aquatic insect family composition in the Chaliyar River ($\chi^2 = 477.13$, df = 74, $p < 0.001$), indicating marked variation in community composition among the pre-monsoon, monsoon, and post-monsoon seasons. Similarly, the Kruskal–Wallis test showed significant seasonal variation in total aquatic insect abundance (H = 15.52, df = 2, $p < 0.001$).

Alpha Diversity Analysis

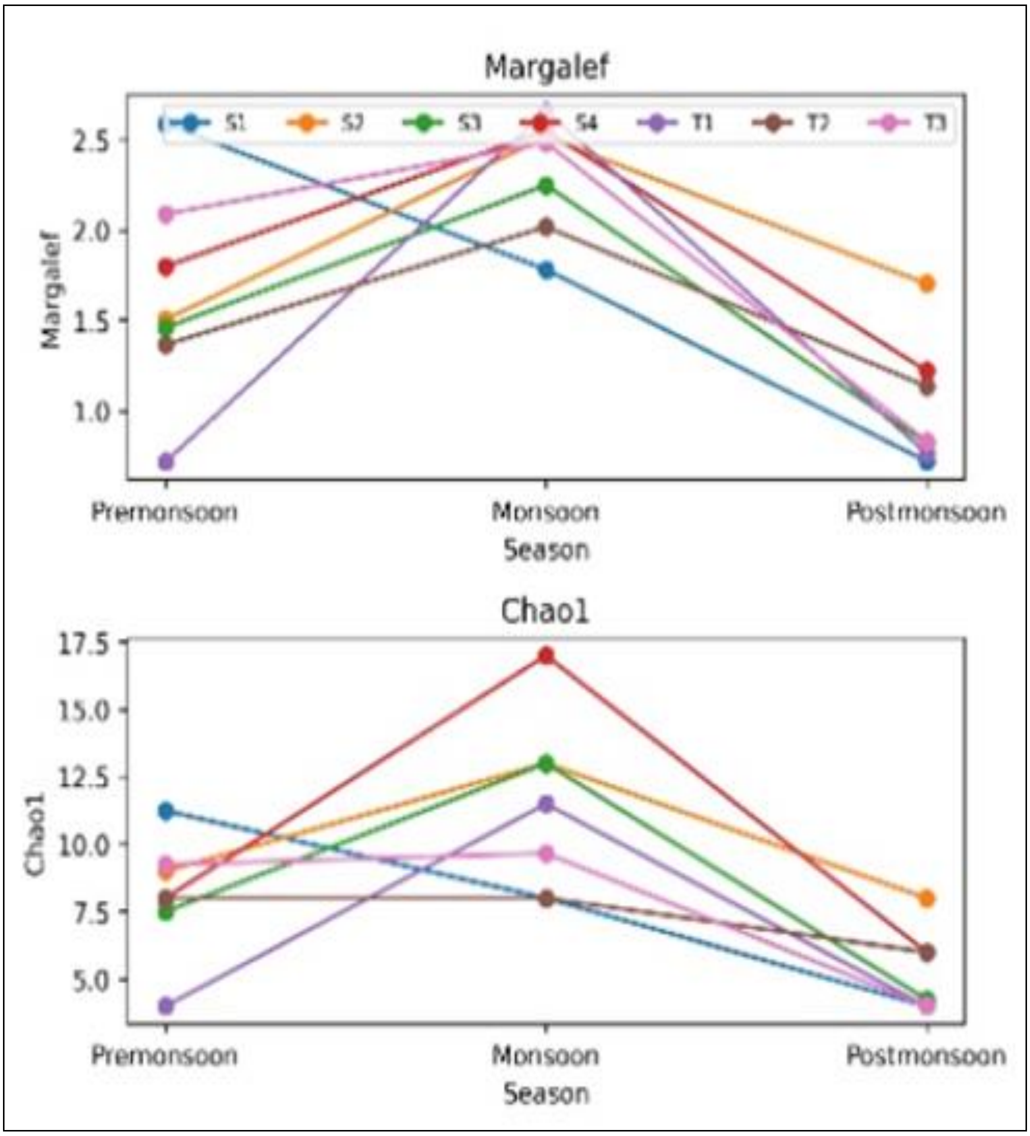
1. Seasonal Variation in Diversity Indices

Alpha diversity indices varied across sampling sites and seasons (Table 2; Fig 4). Margalef richness ranged from 0.716 to 2.659, Chao1 richness from 4 to 17, Shannon diversity from 0.518 to 2.059, Simpson diversity from 0.234 to 0.867, and Pielou's evenness from 0.374 to 0.984.

Seasonal differences were significant for Margalef richness (H = 7.56, $p = 0.023$) and Chao1 richness (H = 6.81, $p = 0.033$). In contrast, Shannon diversity (H = 4.16, $p = 0.125$), Simpson diversity (H = 1.40, $p = 0.496$), and Pielou's evenness (H = 0.17, $p = 0.921$) did not differ significantly among seasons.

Table 2: Seasonal variation in biodiversity indices of aquatic insect communities recorded at sampling sites in the Chaliyar River during 2023.

2023						
Season	Site	Margalef	Chao1	Shannon	Simpson	Pielou
Premonsoon	T1	0.716	4	1.011	0.584	0.729
Premonsoon	T2	1.365	8	1.275	0.636	0.712
Premonsoon	T3	2.09	9.25	1.78	0.759	0.81
Premonsoon	S1	2.588	11.25	2.059	0.86	0.937
Premonsoon	S2	1.504	9	1.672	0.781	0.804
Premonsoon	S3	1.46	7.5	1.573	0.744	0.808
Premonsoon	S4	1.799	8	1.862	0.811	0.895
Monsoon	T1	2.659	11.5	1.959	0.784	0.817
Monsoon	T2	2.02	8	2.045	0.867	0.984
Monsoon	T3	2.485	9.667	2.022	0.845	0.92
Monsoon	S1	1.782	8	1.384	0.623	0.711
Monsoon	S2	2.517	13	1.907	0.812	0.868
Monsoon	S3	2.25	13	1.554	0.668	0.707
Monsoon	S4	2.551	17	1.922	0.813	0.875
Postmonsoon	T1	0.763	4	1.151	0.613	0.831
Postmonsoon	T2	1.135	6	1.417	0.7	0.791
Postmonsoon	T3	0.831	4	1.259	0.687	0.908
Postmonsoon	S1	0.719	4	0.61	0.297	0.44
Postmonsoon	S2	1.703	8	1.889	0.829	0.908
Postmonsoon	S3	0.819	4.25	0.518	0.234	0.374
Postmonsoon	S4	1.221	6	1.747	0.818	0.975



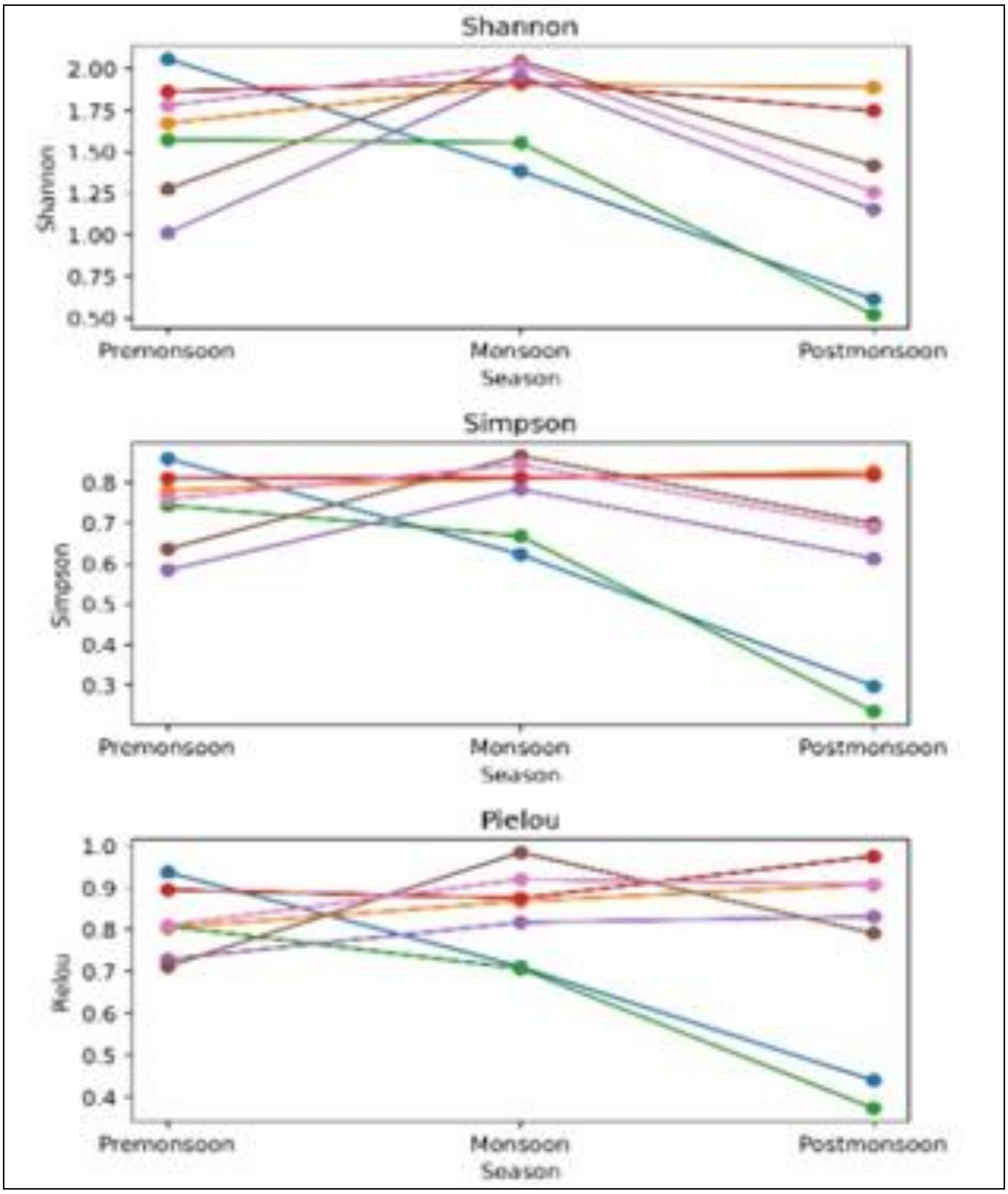


Fig 4. Seasonal variation in Margalef, Chao1, Shannon, Simpson, and Pielou diversity indices across sampling sites during the pre-monsoon, monsoon, and post-monsoon seasons in the Chaliyar River (2023).

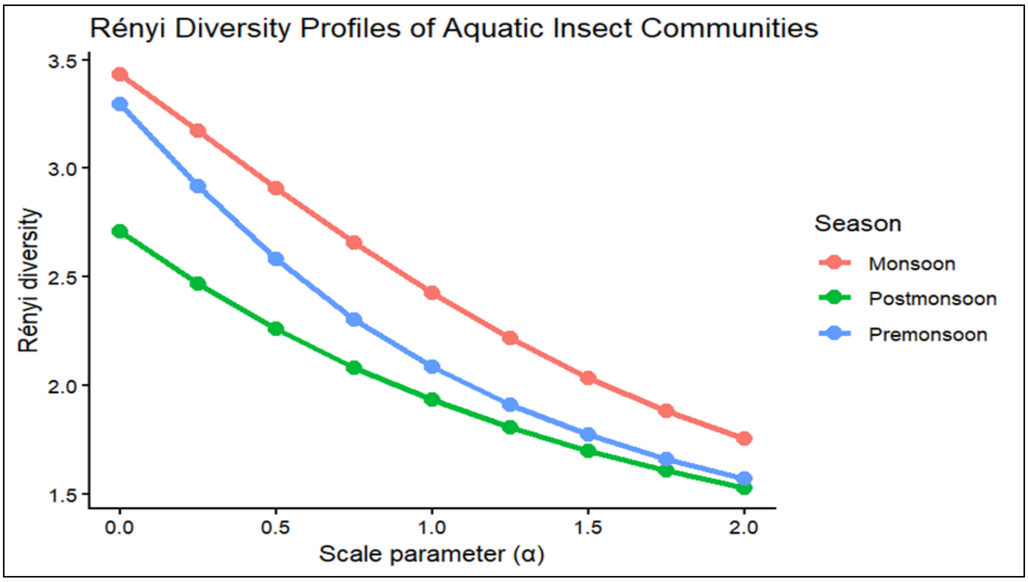


Fig 5: Rényi diversity profiles of aquatic insect communities across the pre-monsoon, monsoon, and post-monsoon seasons in the Chaliyar River.

Dunn's Post-hoc Comparisons of Alpha Diversity

Dunn's post-hoc test with Bonferroni correction revealed significant differences between the monsoon and post-monsoon seasons for Margalef richness ($Z = 2.75$, $p = 0.018$) and Chao1 richness ($Z = 2.61$, $p = 0.027$). No significant pairwise differences were observed between the remaining seasonal comparisons for Shannon diversity, Simpson diversity, and Pielou's evenness.

Permanova of Seasonal and Spatial Effects on Alpha Diversity

PERMANOVA revealed a significant effect of season–site grouping on alpha diversity ($F = 3.65$, $R^2 = 0.709$, $p = 0.023$).

Rényi Diversity Profiles

Rényi diversity profiles indicated the highest diversity during the monsoon across all scale parameters (α), followed by the pre-monsoon and post-monsoon seasons. Diversity values decreased with increasing α, although the relative ordering of seasonal diversity remained consistent (Fig 5).

Hill Diversity

Hill diversity profiles showed the highest effective number of aquatic insect families during the monsoon for $q = 0$, $q = 1$, and $q = 2$, followed by the pre-monsoon and post-monsoon seasons (Fig 6).

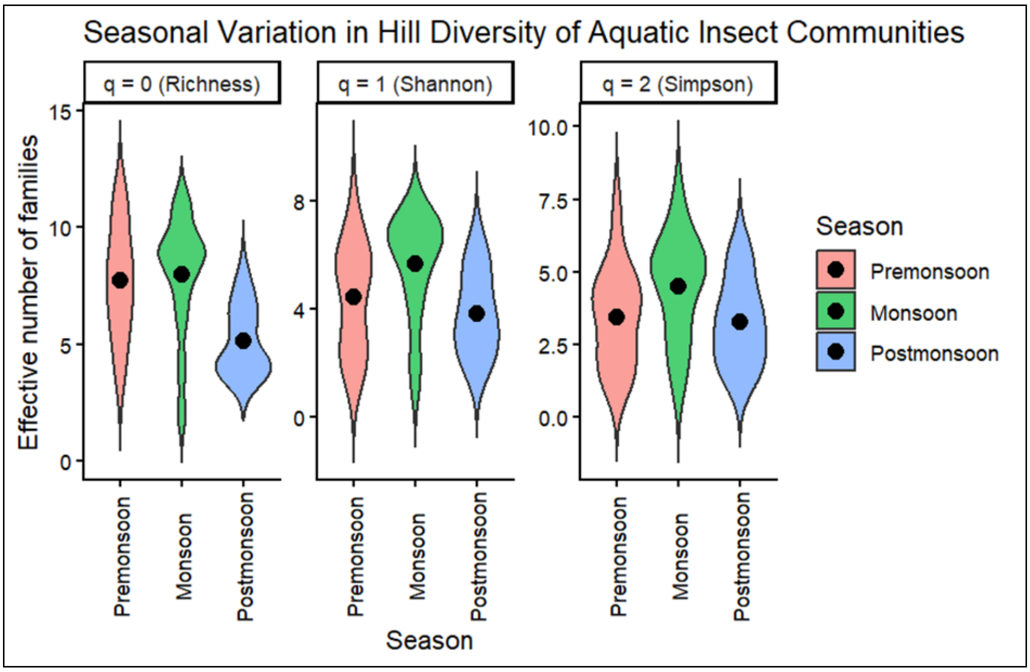


Fig 6. Seasonal variation in Hill diversity ($q = 0$, $q = 1$, and $q = 2$) of aquatic insect communities in the Chaliyar River. Black points indicate mean values.

Discussion

1. Community Structure and Spatial Heterogeneity

The aquatic insect assemblage of the Chaliyar River was dominated by Odonata, particularly Gomphidae, indicating the availability of suitable benthic habitats with sandy and rocky substrates that support burrowing and predatory larvae (Sor, 2017) [26]. In contrast, the relatively low abundance of pollution-sensitive taxa such as Ephemeroptera suggests localised environmental stress despite the generally favourable ecological condition of the river. Similar patterns have been reported from freshwater ecosystems affected by anthropogenic disturbances (Athulya *et al*., 2025) [4].

Seasonal hydrological fluctuations strongly influenced community structure. The decline in aquatic insect abundance during the monsoon, coupled with increased taxonomic richness, suggests that high river discharge disturbed dominant taxa while creating opportunities for the occurrence of less abundant families. Similar responses of aquatic macroinvertebrate communities to seasonal flow disturbances have been documented in tropical river systems (Naveena *et al*., 2023; Kelso & Entrekin, 2017) [13, 17]. The increase in abundance during the post-monsoon further indicates rapid recolonisation of habitats following flood disturbance.

Distinct differences in family composition among sampling sites demonstrate considerable spatial heterogeneity within the Chaliyar River. Variations in habitat complexity, substrate characteristics, and tributary inputs are likely to have contributed to these patterns, as reported for freshwater macroinvertebrate communities in other river systems (Hepp *et al*., 2012; Bo *et al*., 2020; Zhang *et al*., 2021) [9, 12]. The hierarchical clustering analysis further supported this pattern by grouping sites with similar assemblage composition while separating those with distinct community structures. Such clustering is consistent with the influence of habitat characteristics and physicochemical gradients on aquatic insect distribution (Kyerematen *et al*., 2014; De *et al*., 2021; Nieto *et al*., 2017) [14, 18].

The observed patterns indicate that the combined influence of seasonal hydrological dynamics and local habitat heterogeneity structures aquatic insect assemblages in the Chaliyar River. These findings reinforce the value of aquatic insects as reliable indicators of freshwater ecosystem condition and highlight the importance of maintaining habitat diversity for conserving tropical river biodiversity (Li *et al*., 2025).

4.2 Seasonal Variation in Aquatic Insect Diversity

The significant seasonal differences in community composition and abundance indicate that hydrological variability is a primary driver of aquatic insect assemblages in the Chaliyar River. Increased river discharge during the monsoon is likely to disturb benthic habitats and alter substrate stability, resulting in reduced abundance but increased taxonomic richness through the recruitment or persistence of less dominant taxa. Similar seasonal responses have been reported for tropical freshwater macroinvertebrate communities, where flow fluctuations strongly influence habitat availability and community structure (Naveena *et al*., 2023; Athulya *et al*., 2025; Li *et al*., 2025) [4, 17].

The alpha diversity analyses further demonstrated that richness varied significantly among seasons, whereas Shannon diversity, Simpson diversity, and Pielou's evenness remained comparatively stable. This pattern suggests that seasonal changes primarily affected taxonomic richness rather than the overall distribution of individuals among families. Comparable patterns have been observed in freshwater ecosystems where seasonal habitat heterogeneity increases the occurrence of additional taxa without substantially altering community evenness (Castro-Cubillos *et al*., 2022; Pandey *et al*., 2022; Palit & Das, 2020) [7, 20, 21].

PERMANOVA further confirmed that both seasonal variation and site-specific conditions contributed significantly to diversity patterns, highlighting the combined influence of temporal and spatial environmental heterogeneity on aquatic insect assemblages (Slobodchikoff & Parrott, 1977; Pillai *et al*., 2016) [22, 25]. Likewise, the Rényi and Hill diversity profiles consistently showed higher diversity during the monsoon, suggesting that seasonal flow variability enhances habitat heterogeneity and resource availability, thereby supporting a richer and more balanced aquatic insect community (Gao *et al*., 2021; Ashtankar *et al*., 2025; Ongh *et al*., 2024; Shimadzu *et al*., 2013) [2, 9, 19, 24].

These findings demonstrate that seasonal hydrological dynamics are fundamental in structuring aquatic insect diversity in the Chaliyar River, emphasising the importance of incorporating seasonal variability into freshwater biomonitoring and conservation programmes.

Conclusion

This study demonstrates pronounced spatial and seasonal variation in aquatic insect assemblages in the Chaliyar River, driven primarily by monsoon-mediated hydrological dynamics and local habitat heterogeneity. The dominance of Odonata indicates the presence of suitable benthic habitats, whereas the low occurrence of pollution-sensitive taxa suggests localised environmental stress. Seasonal patterns revealed reduced abundance but increased taxonomic richness during the monsoon. These findings highlight the importance of seasonal flow regimes in shaping aquatic insect communities and maintaining biodiversity in tropical river ecosystems. Incorporating seasonal variability into biomonitoring programmes will improve ecological assessments and support the conservation and management of freshwater ecosystems in the Western Ghats.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors utilized generative AI tools to refine the manuscript's language and correct grammatical errors. Following the use of these tools, the authors thoroughly reviewed, verified, and edited the final content as necessary and take full responsibility for the integrity and accuracy of the published article.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Shamiyath Arayilakath conceived and designed the study, carried out field sampling and laboratory analyses, performed data analysis and interpretation, and prepared the original draft of the manuscript. Karimampoyil Shakthidas Anoop Das provided supervision, contributed to manuscript editing and critical revision, and approved the final version of the manuscript.

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