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# Arthropod diversity of Nunia river (West Bengal, India): Impacted by ecological and water quality parameters with water velocity serving as a secondary driver in a pollution-dominated system

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**ABSTRACT**

Urban tropical rivers often experience interacting gradients of pollution and flow, yet the relative influence of water velocity on ecological responses remains poorly understood. This study assessed how water-quality degradation and velocity variation structure aquatic arthropod assemblages in the Nunia River, a small tributary of the Damodar in eastern India. Six sites spanning upstream rural reaches, a midstream urban-industrial corridor, and a downstream confluence were sampled bi-monthly over two years. Physicochemical variables (pH, TDS, EC, DO, BOD, COD, nitrate, phosphate), surface velocity, and aquatic arthropods were quantified; diversity indices and non-parametric and Kruskal-Wallis tests, together with Spearman correlations, were used to explore spatial and seasonal patterns. Water quality parameters showed a pronounced longitudinal gradient. Upstream sites maintained low organic loads, moderate nutrients, and stable DO, whereas midstream sites exhibited severe organic and nutrient enrichment, with critically low DO and elevated COD, BOD, nitrate, and phosphate. COD at the most polluted midstream site reached 74-77 mg/L in summer, while DO dropped to as low as 0.34 mg/L at Site 4. Nitrate peaked at 69.5 mg/L during winter, and phosphate exceeded 6 mg/L in the industrial stretch. Downstream, partial chemical recovery occurred, but nutrient levels remained high. Velocity varied seasonally, with the highest flows in the monsoon and reduced flows in summer and winter; however, velocity showed weak, non-significant relationships with water-quality variables, indicating that pollution inputs rather than hydrology determined chemical conditions. In contrast, arthropod assemblages responded strongly to pollution gradients: diverse communities with crustaceans and hemipterans occurred upstream, while midstream sites were dominated by tolerant Diptera and exhibited low diversity and evenness. Shannon diversity declined from 3.53 at the upstream control site to 0.81 at the most polluted midstream site. Downstream assemblages indicated partial recovery. Overall, water velocity acted as a secondary disturbance factor, whereas spatially concentrated anthropogenic pollution emerged as the primary driver of ecological degradation in the Nunia River.

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## INTRODUCTION

Freshwater ecosystems in tropical regions support an extraordinary diversity of aquatic insects, organisms that not only dominate lotic and lentic habitats numerically but also functionally. Globally, nearly 45,000 species of aquatic insects have been described, accounting for about 3% of all insect species (Balaram, 2005). In India, an estimated 5,000 species occupy diverse freshwater habitats ranging from rivers and streams to ponds, lakes, and marshes (Subramanian and Sivaramakrishnan, 2007). These insects play essential ecological roles within aquatic food webs as herbivores, detritivores, and predators, contributing significantly to nutrient recycling and the overall functioning and stability of freshwater ecosystems (Daly *et al.*, 1998; Dijkstra *et al.*, 2014). Their high reproductive output, rapid generation time, and strong colonization capacity enable aquatic insects to dominate many tropical freshwater habitats, particularly nutrient-rich lentic environments (Roy *et al.*, 1988). Owing to these attributes, they have become widely used as model organisms in biomonitoring studies, where their community structure provides reliable indicators of human-induced changes in freshwater ecosystems (Rosenberg and Resh, 1988; Balachandran *et al.*, 2012; Bonada *et al.*, 2006). In India, the application of aquatic insects alongside physicochemical parameters to evaluate water quality has gained prominence in recent years, with multiple studies demonstrating that assemblage composition reliably reflects prevailing environmental conditions of freshwater habitats (Barman *et al.*, 2014; Jose and Cherian, 2019; Chakravarty and Gupta, 2021; Mukherjee and Paramanik, 2024).

Aquatic and riparian arthropods form a vital link between environmental quality and ecosystem functioning, and their community structure closely mirrors variations in flow, substrate, and water chemistry, making them indispensable biological indicators of river health. Evidence from Amazonian and European floodplains shows that species richness peaks in uplands and declines with increasing flood stress, reflecting differential tolerance to inundation and habitat instability (Wittmann *et al.,* 2022). Habitat specialization is pronounced across groups: mites, springtails, and termites occupy well-defined microhabitats, whereas beetles and spiders frequently dominate disturbed channel margins. Although still emerging, Indian research underscores comparable patterns. In the Alaknanda River of Uttarakhand, Rana *et al.* (2017) reported nine orders, 53 families, and 73 genera, with Diptera and Trichoptera contributing substantially to overall richness. Rao (2001) documented 58 species across 17 families in the upper Ganga, including several pollution-sensitive Ephemeroptera, Plecoptera, and Trichoptera taxa. Similarly, the Tawi River supports insect orders indicative of well-oxygenated waters (Chowdhary and Sharma, 2013). In the northeast, Hemiptera dominated pre-monsoon assemblages in the Brahmaputra (Gogoi and Gupta, 2017), while the Jatinga River exhibited eight orders and 25 families with sharp contrasts between mid- and downstream communities (Chakravarty and Gupta, 2021). Peninsular systems, including the Tapi, Chandrabhaga, and Godavari, also sustain diverse assemblages, with the latter supporting 47 taxa across nine orders (Nair *et al.,* 2023; Sharma *et al.,* 2008; Shrestha, 2006). Functional relationships between water chemistry and arthropod abundance further illustrate the mechanistic basis of bioindication: Pal *et al.* (2012) observed *Gerris spinolae* thriving in oxygen-rich waters, whereas *Brachydeutera longipes* proliferated under elevated BOD, phosphate, and free $CO_2$, demonstrating species alignment along pollution-sensitivity gradients. Recent ecological assessments emphasize functional traits-respiration mode, feeding guild, dispersal ability, and cuticular permeability- as critical predictors of stress tolerance, with collector-gatherers and filter-feeders dominating organically enriched zones while predators and scrapers decline as turbidity and nutrient loads increase (Loureiro *et al.*, 2023). Not only do the creatures live directly in the waterbodies, but considerable faunal diversity also lives in association with them, which may be impacted by pollution (Roy *et al.*, 2021; Mukherjee *et al.*, 2022). Global studies, including those from South and Southeast Asia (Fernando, 1963; Freitag, 2005), integrate multivariate ordination approaches to disentangle how dissolved oxygen (DO), conductivity, heavy-metal concentrations, and nutrient enrichment jointly influence arthropod distribution, revealing that chemical stressors rarely operate in isolation but interact synergistically to restructure assemblages along longitudinal and seasonal gradients (Leland *et al.*, 1986).

Anthropogenic activities, such as ritual-driven pollution and non-sustainable usages, have been shown to alter nutrient dynamics, turbidity, and organic load in receiving water bodies (Roy and Paramanik, 2022; Mukherjee and Paramanik, 2022), underscoring the need to integrate cultural stressors into aquatic bioassessment. Despite the wealth of physicochemical research in India, comprehensive studies linking water-quality variables to arthropod community patterns remain limited, and only a few preliminary assessments have examined water quality in the Nunia River in recent years (Mukherjee and Paramanik, 2023, 2025). The present investigation on the Nunia River, a tributary of the Damodar in Paschim Bardhaman, builds upon this body of knowledge by integrating diversity indices with ordination analyses to relate key parameters, including DO, BOD, COD, nutrients, and metals, to arthropod abundance and indicator taxa. Insights drawn from previous literature will provide the conceptual and methodological foundation for establishing a site- and season-specific framework for assessing and monitoring the ecological health of the Nunia River.

In flowing-water ecosystems, water current velocity is a primary factor shaping the structure and distribution of resident animal communities. Classical experimental work by Zimmerman (1961a, 1961b) demonstrated that identical water chemistry can produce entirely different aquatic insect communities when current speed varies. Hynes (1972) emphasized that current velocity controls both the occurrence and abundance of aquatic species, a pattern linked to morphological adaptations, respiratory requirements, and behaviour. According to Nielsen (1950), streams averaging ≥0.5 m/s may be considered 'fast streams', typically characterized by alternating riffles and pools. Riffles generally exhibit coarse substrates and high flow (>0.5 m/s), functioning as zones of primary production (Nelson and Scott, 1962), whereas pools consist of slower or standing water with fine sediments and are sites of oxidation and decomposition (Neel, 1951). Consistent with this habitat contrast, several early investigations report higher abundance, biomass, and species richness in riffles than pools (Surber, 1939; Lyman and Dendy, 1943; O'Connell and Campbell, 1953).

Against this well-established ecological background, the Nunia River, a tropical tributary of the Damodar in eastern India, presents a compelling but understudied system. As the river flows through rural settlements, peri-urban landscapes, and industrial outskirts, it undergoes pronounced shifts in current velocity from fast-flowing upstream reaches (Sites 1 and 2) to slow-flow depositional midstream stretches (Sites 3, 4, and 5), before merging with the Damodar at the downstream confluence (Site 6). Reviews highlight that acid-mine drainage and coal-belt runoff continue to introduce sulphates, iron, and trace metals into tributaries (Mukherjee *et al.,* 2024a), making biological assessment particularly crucial. Episodes of detergent-rich foam formation documented in the Nunia River (Mukherjee *et al.,* 2024b) further indicate the interaction between hydrodynamics, surfactants, and organic pollution. These hydrological transitions interact with domestic wastewater discharge, organic loading, and urban runoff, creating distinct physicochemical conditions expected to influence aquatic insect assemblages. Despite its ecological and societal importance, no detailed assessment has examined how flow variation and pollution jointly influence aquatic insect communities in the Nunia River. Understanding these relationships is essential for developing a baseline for future biomonitoring in small tropical rivers.

The present study therefore aims to: (i) document the spatial and seasonal variation in aquatic arthropod assemblages along the Nunia River and identify changes across pollution gradients; (ii) examine how physicochemical parameters shape arthropod community structure and determine whether water velocity plays a primary or secondary role in influencing water quality and biodiversity; (iii) evaluate the applicability of classical flow ecology relationships in a tropical, pollution-dominated river and determine whether anthropogenic stress overrides hydrological control.

## MATERIALS AND METHODS

### Study area and sampling sites

Asansol, the administrative center of Paschim Bardhaman district in West Bengal, lies along the Nunia River, which traverses the city before joining the Damodar system. As the second-largest urban agglomeration in the state, Asansol encompasses several densely populated neighbourhoods, such as Kalyanpur, Chandmari Danga, Jahangiri Moholla, and Qureshi Moholla, situated near the river. The Nunia originates near Samdi in Paschim Bardhaman (23°80′34″N, 86°89′06″E) and flows southward, entering the Asansol region near Miliakhola (also known as Melakola). It continues past Kalipahari and ultimately merges with the Damodar River near Raniganj (23°59′32″N, 87°09′35″E) (Fig. 1). Functionally, the Nunia serves as an essential hydrological component for the region, supporting both domestic and commercial activities. Residents depend on the river for everyday purposes such as washing, bathing, livestock management, irrigation, and other household uses. Numerous small-scale industries, including beverage manufacturing, paint and bakery units, and brick-making facilities, are also concentrated along its banks. Moreover, the river forms a major drainage conduit, carrying stormwater and urban runoff through the city. Given the heavy reliance on this watercourse, maintaining its quality is critical for safeguarding community health and supporting sustainable regional development. To evaluate the physicochemical condition of the river, six monitoring sites were strategically selected along its course (Fig. 1), with their locations and characteristics summarised in Table 1.

**Fig. 1.** Map showing the six sampling sites (S1–S6) along the Nunia River, illustrating the upstream, midstream, transitional, and confluence zones within the Asansol-Raniganj region

### Sample collection

*Water*

A two-year bi-monthly sampling programme was carried out at six locations along the Nunia River. To ensure accuracy and avoid contamination, water samples were collected using sterile, screw-capped flasks at a depth of approximately 15 cm below the surface, thereby reducing interference from floating debris or surface disturbances. After collection, the samples were transported to the laboratory under chilled conditions and stored at 4°C to retain their physicochemical attributes until analysis. Field measurements of electrical conductivity (EC), pH, and total dissolved solids (TDS) were recorded on-site using a Hanna Instruments HI98130 multiparameter meter to obtain instantaneous values. Additional water quality parameters (WQP), including dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrate, and phosphate, were analysed in the laboratory following the standard procedures outlined by APHA (2005). Each analysis was done in triplicate.

**Table 1.** Geographic location, site codes, coordinates, and flow characteristics of the six sampling stations along the Nunia River.

| Sampling location | Site code | Geographical coordinates (Lat-Long) | Flow condition |
|---|---|---|---|
| Alkusha | S1 | 23°48′00″N, 86°53′16″E | Rapid upper-reach flow |
| Melakola | S2 | 23°44′32″N, 86°53′59″E | Swift upstream current |
| Kalyanpur | S3 | 23°41′58″N, 86°57′21″E | Sluggish mid-reach flow |
| Dipupara | S4 | 23°41′39″N, 86°59′10″E | Slow-moving transitional zone |
| Kalipahari | S5 | 23°40′34″N, 87°00′52″E | Reduced-velocity midstream |
| Mohana | S6 | 23°35′30″N, 87°05′37″E | Mixed-flow confluence zone |

*Arthropods*

Simultaneously, an arthropod sampling programme was conducted to assess the diversity of aquatic and semi-aquatic arthropods across different flow regimes and seasons. The littoral margins were surveyed with a 30 × 30 cm sweep net fitted with a 500-µm mesh, following the methodologies described by Macan and Maudsley (1968) and Brittain (1974). For mid-channel and downstream habitats, a 180-µm kick-net was employed, based on protocols adapted from Brittain (1974) and Subramanian and Sivaramakrishnan (2007). During peak monsoon discharge, when conventional netting becomes challenging, an intensive hand-search method was adopted, covering an area of approximately 10 m² for one hour and sampling arthropods from stones, submerged vegetation, leaf litter, and other microhabitats. Collected material was washed, sorted at the site, and preserved using either 70% ethanol or buffered formalin, depending on downstream taxonomic requirements. Identification of specimens was undertaken in the laboratory using stereo-zoom microscopes and standard freshwater arthropod and insect identification manuals (Edmondson, 1959; Buck *et al.,* 2009; Subramanian and Sivaramakrishnan, 2007; Richard and Davies, 2013). This combined use of sweep-netting, kick-sampling, and systematic manual searching ensured a comprehensive representation of the arthropod assemblages present in the Nunia River. To maintain consistency across sampling events and ensure comparability among sites, a uniform sampling effort was applied throughout the study. At each of the six sites, three replicate samples were collected at each bi-monthly visit using identical sweep-net and kick-net procedures. Each replicate represented an independent sampling unit covering a fixed search effort of 10 minutes for sweep-netting along littoral margins and five minutes of active disturbance for kick-sampling in mid-channel sections. During monsoon months, when standard netting was less feasible, the manual all-out search followed a strictly defined protocol of one hour of continuous sampling across a 10 m² area, ensuring temporal and spatial effort remained standardised regardless of hydrological variation. All sampling was conducted between 09:00 and 13:00 hrs to minimise diel variability in arthropod activity and habitat use. Equipment was cleaned between sites to prevent cross-contamination or transfer of organisms.

**Water velocity measurement**

Water velocity at each sampling location was measured using the conventional surface-float method, which is appropriate for shallow, small to medium-sized tropical rivers (CSWRCB, 2018). A lightweight wooden piece, selected for its buoyancy and natural visibility, was gently released upstream of a marked 10 m transect. The time required for the float to travel the measured distance was recorded with a stopwatch. This procedure was repeated three times per site, and the mean value was used to calculate surface flow velocity. This method provided a simple, cost-effective, and consistent means of categorizing sites into fast-flowing, slow-flowing, and confluence-mixed zones along the Nunia River.

**Statistical analysis**

A structured statistical framework was applied to examine spatial and seasonal variations in water quality and arthropod diversity across the Nunia River. Descriptive statistics (mean, standard deviation, and range) were first used to summarise physicochemical variables and diversity indices. The relationships among key WQP and among biodiversity metrics were evaluated using Spearman's rank correlation, which is appropriate for non-parametric ecological data. To test spatial and seasonal differences in arthropod diversity, Kruskal-Wallis one-way ANOVA was employed, as it provides reliable results when group variances are unequal, followed by comparisons of site and seasonal effects on Simpson dominance, Gini-Simpson, Shannon diversity, and evenness. The influence of river velocity on individual WQP was assessed using univariate ANOVA, while the combined multivariate effect of velocity on the full suite of physicochemical variables was tested using multivariate statistics (Pillai's Trace, Wilks' Lambda). These methods collectively provided a robust analytical basis for identifying dominant ecological gradients and determining the extent to which hydrological and pollution-related factors shape the chemical and biological structure of the river. All computations were performed using PAST v4.13, Jamovi, and SPSS v26, with significance set at $p<0.05$ (R Core Team, 2024; The Jamovi Project, 2024). This multi-analytical framework will provide an integrated assessment of how environmental conditions, hydrological characteristics, and pollution gradients structure arthropod communities in the Nunia River.

## RESULTS

### River water quality parameters

Water quality parameters (WQP) across the Nunia River displayed clear spatial variability among the six study sites, with distinct seasonal fluctuations superimposed upon geographic trends (Table 2). pH remained generally neutral throughout the system but showed noticeable differences between sites, with Site 3 exhibiting slightly higher values during monsoon (7.41) compared to the lower pH recorded at Site 4 (6.89), while Site 6 showed a gradual rise from monsoon to winter (6.94-7.38). TDS and EC revealed a consistent pattern of increasing concentration from upstream toward the central sites; for instance, monsoon TDS increased from 196 mg/L at Site 1 to around 300 mg/L at Sites 4-5, before declining at Site 6 (218 mg/L), while EC values followed a similar trend, reaching highest levels at central sites such as Site 4 (591 µS/cm) and Site 5 (483 µS/cm) during monsoon. Summer amplified these gradients; with Site 2 recording exceptional TDS (632 mg/L) and EC (1205 µS/cm) values compared to the comparatively lower summer readings at Site 1 (277 mg/L TDS; 553 µS/cm EC). DO varied sharply across the river, with Sites 1 and 2 maintaining the highest DO in all seasons (around 5.3-6.6 mg/L), while Sites 4 and 5 showed the lowest values, particularly in summer, where DO fell to 0.336 mg/L at Site 4 and 1.498 mg/L at Site 5. These differences highlight the central reach as the most oxygen-depleted section compared to the more oxygen-rich upstream and downstream points. Nutrient dynamics showed even stronger contrasts: nitrate concentrations were moderate upstream (e.g., Site 1: 12.6-44.17 mg/L across seasons) but markedly higher at Site 4, which exhibited the highest nitrate in winter (69.51 mg/L), indicating significant nutrient enrichment at this location. Summer nitrate was highest at Site 6 (40.52 mg/L), showing that the downstream confluence zone also experienced nutrient loading. Phosphate values mirrored the nitrate pattern, with Sites 4 and 5 showing pronounced enrichment (up to 6.37 mg/L in summer at Site 4), while upstream Sites 1 and 2 retained very low phosphate levels (<1 mg/L), demonstrating substantial spatial contrast in nutrient inflow. Organic pollution indicators provided the clearest cross-site differentiation: COD and BOD were lowest at Sites 1 and 2 in all seasons, but increased rapidly toward the central sites, where monsoon COD peaked at 47.5 mg/L (Site 4) and winter COD exceeded 74 mg/L at Site 5. BOD exhibited the strongest spatial divergence, with the highest values concentrated at central sites: 20.5 mg/L (Site 4, summer), 26.75 mg/L (Site 5, summer), and the maximum winter value of 31.5 mg/L (Site 4) compared to considerably lower upstream BOD (68 mg/L). Downstream at Site 6, moderate recovery in DO and reductions in COD/BOD were visible, although nitrate and phosphate remained elevated compared to the upstream sections. Taken together, the cross-site comparison reveals a clear longitudinal gradient: Sites 1 and 2 consistently showed the most stable water-quality conditions; Sites 3-5 represented the most degraded segment, with substantial nutrient and organic loading; and Site 6 reflected a mixed condition influenced by both upstream pollution transport and input from the adjoining river.

Across seasons, the Nunia River exhibited pronounced fluctuations in its physicochemical parameters, demonstrating the strong influence of monsoon rainfall, summer concentration effects, and winter stagnation on water quality. During the monsoon, most parameters appeared diluted: TDS and EC remained relatively lower at several sites due to increased runoff, while DO generally remained higher at the upstream and downstream locations, although critically low values persisted in the central sites despite seasonal flushing. Nutrient concentrations such as nitrate and phosphate showed moderate values in the monsoon at most sites, except midriver locations where phosphate remained persistently elevated. In summer, sharp increases in TDS, EC, nitrate, phosphate, COD, and BOD were observed throughout the river, with the central sites exhibiting the most pronounced seasonal intensification. Summer DO levels drop significantly, especially at Sites 4 and 5, indicating stronger oxygen depletion driven by elevated temperatures and reduced water volume. Winter conditions further accentuated nutrient and organic pollution, with nitrate reaching peak levels (e.g., 69.51 mg/L at Site 4) and COD and BOD remaining high across the midriver region. Although DO improves slightly in winter when compared to summer at some locations, oxygen depletion persisted in the central sites. Overall, seasonal comparisons reveal that the monsoon exerts a diluting effect on many parameters, summer promotes concentration of pollutants due to reduced flow and higher evaporation, and winter further intensifies nutrient and organic accumulation, especially in the central portion of the river.

**Table 2.** Seasonal variation of key water-quality parameters recorded across six sites of the Nunia River during monsoon, summer, and winter

| Season | Site | pH | TDS | EC | DO | Nitrate | Phosphate | COD | BOD |
|---|---|---|---|---|---|---|---|---|---|
| Monsoon | 1 | 7.02 | 196 | 394 | 5.41 | 12.6 | 0.932 | 27.4 | 8.47 |
| | 2 | 7.20 | 306 | 614 | 5.75 | 21.3 | 0.62 | 31.3 | 7.95 |
| | 3 | 7.41 | 283 | 566 | 5.04 | 18.9 | 2.07 | 17.7 | 3.75 |
| | 4 | 6.89 | 295 | 591 | 1.25 | 15.6 | 2.69 | 47.5 | 13.9 |
| | 5 | 7.09 | 300 | 483 | 3.37 | 12.3 | 2.09 | 33.2 | 9.55 |
| | 6 | 6.94 | 218 | 408 | 4.66 | 20.2 | 2.43 | 20.0 | 6.0 |
| Summer | 1 | 7.13 | 277 | 553 | 5.41 | 2.97 | 0.67 | 19.3 | 6.08 |
| | 2 | 7.20 | 632 | 1205 | 5.42 | 22.6 | 0.643 | 12.7 | 2.25 |
| | 3 | 7.08 | 321 | 625 | 3.16 | 9.04 | 1.89 | 32.3 | 9.30 |
| | 4 | 6.73 | 409 | 800 | 0.336 | 16.4 | 6.37 | 74.0 | 20.5 |
| | 5 | 7.03 | 340 | 610 | 1.50 | 17.3 | 4.83 | 77.4 | 26.8 |
| | 6 | 7.15 | 354 | 705 | 4.21 | 40.5 | 2.68 | 35.9 | 13.5 |
| Winter | 1 | 7.14 | 285 | 578 | 5.33 | 4.17 | 0.878 | 20.4 | 7.13 |
| | 2 | 7.04 | 416 | 840 | 6.62 | 20.6 | 0.538 | 11.8 | 4.07 |
| | 3 | 7.17 | 356 | 699 | 5.16 | 30 | 1.28 | 15.0 | 7.5 |
| | 4 | 7.08 | 382 | 788 | 1.12 | 69.5 | 4.17 | 66.6 | 31.5 |
| | 5 | 7.06 | 410 | 814 | 1.79 | 24.7 | 5.21 | 74.4 | 27.5 |
| | 6 | 7.38 | 289 | 585 | 5.48 | 33.8 | 2.08 | 17.4 | 4.25 |

Total Dissolved Solids (TDS; mg/L), Electrical Conductivity (EC; µS/cm), Dissolved Oxygen (DO; mg/L), nitrate (mg/L), phosphate (mg/L), Chemical Oxygen Demand (COD; mg/L), and Biological Oxygen Demand (BOD; mg/L).

**River water velocity**

River velocity in the Nunia showed distinct spatial and seasonal variation (Table 3), reflecting the combined influence of monsoon discharge, channel morphology, and localized wastewater inflows. During the monsoon, flow remained consistently high across all sites, with the central reach experiencing the fastest currents due to increased runoff and channel constriction. Summer flows dropped sharply at most sites as water levels declined, although isolated increases occurred where channel narrowing or effluent discharge enhanced local turbulence.

Winter velocities stabilized at moderate levels, remaining lowest in the midstream section where the channel widens and sediment accumulates, while upstream and downstream sites maintained comparatively higher flow. Overall, the velocity pattern illustrates a dynamic hydrological system shaped by natural seasonal rhythms and site-specific geomorphological features.

**Table 3.** Seasonal variation in river-water velocity, recorded at six sampling sites along the Nunia River during the monsoon, summer, and winter seasons

| Season | Site | Velocity (m/S) |
|---|---|---|
| Monsoon | 1 | 0.70 |
| | 2 | 0.96 |
| | 3 | 1.12 |
| | 4 | 1.20 |
| | 5 | 1.01 |
| | 6 | 1.13 |
| Summer | 1 | 0.45 |
| | 2 | 0.42 |
| | 3 | 0.25 |
| | 4 | 0.49 |
| | 5 | 0.96 |
| | 6 | 0.82 |
| Winter | 1 | 0.50 |
| | 2 | 0.56 |
| | 3 | 0.30 |
| | 4 | 0.52 |
| | 5 | 0.99 |
| | 6 | 0.87 |

**Relationship between river velocity patterns and key WQP**

Spatial and seasonal variations in river-water velocity exhibited clear relationships with multiple physicochemical parameters along the Nunia River. During the monsoon, velocities were consistently highest across all sites (0.70-1.20 m/s), coinciding with elevated TDS, EC, and nutrient concentrations, particularly at mid-stream sites (Sites 3-5), where nitrate reached 12.3-21.3 mg/L and phosphate increased up to 2.69 mg/L. The enhanced discharge and runoff during this season likely facilitated the mobilization of dissolved ions and nutrients from adjacent urban and peri-urban catchments. Sites with relatively higher velocities (Sites 3-6) also showed moderate COD and BOD, indicating that rapid flow aided partial dilution of organic loads but did not fully mitigate downstream oxygen stress, especially at Site 4, where DO dropped to 1.25 mg/L despite the higher monsoonal velocity (1.20 m/s). This pattern suggests that velocity-driven flushing interacts with localized pollutant load rather than uniformly controlling it.

In contrast, summer velocities declined sharply at Sites 1-4 (0.25-0.49 m/s), while Site 5 exhibited a local increase (0.96 m/s), reflecting channel geometry and localized discharge inputs. Reduced summer velocities corresponded with pronounced deterioration in organic-pollution indicators at Sites 4 and 5, where COD reached 74-77.4 mg/L and BOD escalated to 20.5-26.8 mg/L. These sites also recorded some of the highest phosphate concentrations (4.83-6.37 mg/L) and markedly low DO (0.33-61.50 mg/L), indicating that diminished flow promoted pollutant retention, reduced reaeration, and the accumulation of untreated sewage and industrial wastewater. Meanwhile, the relatively higher velocity at Site 5 during summer aligned with comparatively moderate DO (1.50 mg/L) and mixed organic-load signals, suggesting that even within a polluted stretch, slight increases in velocity can influence oxygen dynamics and organic-matter transport.

During winter, velocities were moderate (0.30-0.99 m/s) and more uniform across sites, producing a distinct relationship with water quality. Sites with lower velocities (Sites 3-4; 0.30-0.52 m/s) showed disproportionately high nutrient loads, especially nitrate (30-69.5 mg/L), accompanied by elevated COD and BOD (66.6-31.5 mg/L at Site 4). This indicates that low winter velocities support the retention and slow diffusion of agricultural and urban effluents entering the channel during the dry season. Conversely, sites with relatively higher velocities (Sites 1, 5, and 6) maintained comparatively stable DO levels (5.33-5.48 mg/L) and lower COD/BOD, suggesting that moderate flow during winter improves aeration and facilitates downstream export of organic matter.

Across all seasons, the dataset reveals that river velocity acts as a key physical regulator of water-quality dynamics, but its influence is strongly modulated by site-specific pollution intensity. Higher velocities generally correspond with lower organic accumulation and moderate DO, whereas reduced velocities consistently coincide with elevated COD, BOD, phosphate, and extreme nitrate levels, especially at sites receiving concentrated wastewater inputs. However, Site 4 demonstrates that when pollution loads are overwhelming, even higher monsoon velocities fail to improve DO, indicating that hydrology alone cannot counteract heavy organic and nutrient influx. Overall, the interaction between velocity and pollutant load shapes the spatiotemporal water-quality gradients of the Nunia River, playing a crucial role in determining oxygen balance, nutrient retention, and organic-matter decomposition across the fluvial system.

**Table 4.** Spearman correlation matrix showing the relationships among key water-quality parameters and river velocity (m/s) across all sampling sites and seasons of the Nunia River

| | pH | TDS | EC | DO | Nitrate | Phosphate | COD | BOD | Velocity |
|---|---|---|---|---|---|---|---|---|---|
| pH | - | - | - | - | - | - | - | - | - |
| TDS | - 0.019 | - | - | - | - | - | - | - | - |
| EC | 0.029 | 0.961 | - | - | - | - | - | - | - |
| DO | 0.544 | - 0.174 | - 0.109 | - | - | - | - | - | - |
| Nitrate | 0.319 | 0.509 | 0.540 | 0.049 | - | - | - | - | - |
| Phosphate | - 0.470 | 0.141 | 0.082 | - 0.887 | 0.195 | - | - | - | - |
| COD | - 0.518 | 0.129 | 0.071 | - 0.824 | - 0.055 | 0.796 | - | - | - |
| BOD | - 0.523 | 0.247 | 0.176 | - 0.804 | 0.067 | 0.748 | 0.938 | - | - |
| Velocity | - 0.167 | - 0.352 | - 0.401 | - 0.166 | 0.065 | 0.367 | 0.284 | 0.124 | - |

**Table 5.** One-way ANOVA results evaluating the effect of river velocity on individual water-quality parameters (pH, TDS, EC, dissolved oxygen, nitrate, phosphate, COD, and BOD) across the Nunia River ($p$ > 0.05 for all the parameters)

| | Dependent variable | Sum of Squares | df | Mean Square | F | $p$ |
|---|---|---|---|---|---|---|
| Velocity | pH | 6.65E-04 | 1 | 6.65E-04 | 0.02487 | 0.877 |
| | TDS | 22890.429 | 1 | 22890.4291 | 2.74367 | 0.117 |
| | EC | 106508.58 | 1 | 106508.58 | 3.44298 | 0.082 |
| | DO | 1.523 | 1 | 1.5233 | 0.38854 | 0.542 |
| | Nitrate | 0.559 | 1 | 0.5588 | 0.00226 | 0.963 |
| | Phosphate | 2.377 | 1 | 2.3774 | 0.76972 | 0.393 |
| | COD | 307.91 | 1 | 307.9098 | 0.57762 | 0.458 |
| | BOD | 12.932 | 1 | 12.9321 | 0.15373 | 0.700 |
| Residuals | pH | 0.428 | 16 | 0.0267 | | |
| | TDS | 133488.07 | 16 | 8343.0044 | | |
| | EC | 494960.53 | 16 | 30935.0332 | | |
| | DO | 62.727 | 16 | 3.9204 | | |
| | Nitrate | 3948.314 | 16 | 246.7696 | | |
| | Phosphate | 49.419 | 16 | 3.0887 | | |
| | COD | 8529.013 | 16 | 533.0633 | | |
| | BOD | 1345.96 | 16 | 84.1225 | | |

**Statistical tests and interpretation**

The Spearman correlation matrix revealed a clear pattern of strong pollutant-driven relationships in the Nunia River, dominated by two major parameter clusters and the absence of any hydrological influence (Table 4). TDS and EC were almost perfectly correlated (ρ= 0.961), reflecting a shared ionic source, while their moderate positive correlations with nitrate (TDS: ρ= 0.509; EC: ρ= 0.540) indicate that nitrate is a substantial contributor to ionic enrichment along the river. The strongest associations emerged within the organic-pollution and oxygen-depletion complex. DO showed pronounced negative correlations with phosphate (ρ= 0.887), COD (ρ= 0.824), and BOD (ρ= 0.804), confirming that oxygen reduction is tightly linked to elevated organic loads and nutrient enrichment from sewage and urban wastewater inputs. COD and BOD were strongly and positively correlated (ρ= 0.938), reflecting their common origin in untreated domestic waste, while phosphate also displayed strong positive correlations with COD (ρ= 0.796) and BOD (ρ= 0.748), indicating that high nutrient concentrations co-occur with organic pollution. Nitrate exhibited only weak relationships with DO (ρ = 0.049) and phosphate (ρ = 0.195), suggesting that nitrate is more influenced by external runoff and wastewater sources than by internal biochemical processes. River velocity showed uniformly weak and non-significant correlations with all WQP. These weak values clearly demonstrate that natural flow variation does not meaningfully influence the river's chemical condition. Overall, the correlation structure shows that the Nunia River is governed primarily by anthropogenic nutrient and organic pollution, while hydrological velocity plays no measurable role in shaping water-quality dynamics.

The univariate tests (Table 5) evaluated whether river velocity significantly influences individual WQP. Across all eight variables, none showed a statistically significant response to velocity (all $p>0.05$), indicating that flow speed does not meaningfully alter physicochemical conditions in the Nunia River. Although some parameters, such as TDS and EC, displayed numerical differences across velocity ranges, their F-values (TDS: F = 2.74; EC: F = 3.44) did not reach significance ($p$ = 0.117 and $p$ = 0.082, respectively), reflecting only weak tendencies rather than reliable effects. For the remaining parameters, including pH ($p$ = 0.877), DO ($p$ = 0.542), phosphate ($p$ = 0.393), COD ($p$ = 0.458), and BOD ($p$ = 0.700), the influence of velocity was negligible. The residual sums of squares far exceeded the variance explained by velocity, confirming that most water-quality variability arises from site-specific pollution sources rather than hydrological flow variation.

Multivariate tests (Table 6) (Pillai's Trace = 0.44, Wilks' Lambda = 0.56, $p$ > 0.05) indicate that river velocity has no significant multivariate effect on WQP, confirming that pollution inputs dominate the chemical structure of the Nunia River water.

So, the velocity is not a significant predictor of any WQP because the river's chemical conditions are dominated by strong anthropogenic pollution inputs, while the natural variation in flow was too small and too weak to produce measurable effects on physicochemical variables.

**Table 6.** Multivariate test results (Pillai's Trace and Wilks' Lambda) assessing the combined effect of river velocity on the full set of water-quality parameters ($p$ > 0.05)

| | | Value | F | df1 | df2 | $p$ |
|---|---|---|---|---|---|---|
| Velocity | Pillai's Trace | 0.44 | 0.883 | 8 | 9 | 0.564 |
| | Wilks' Lambda | 0.56 | 0.883 | 8 | 9 | 0.564 |

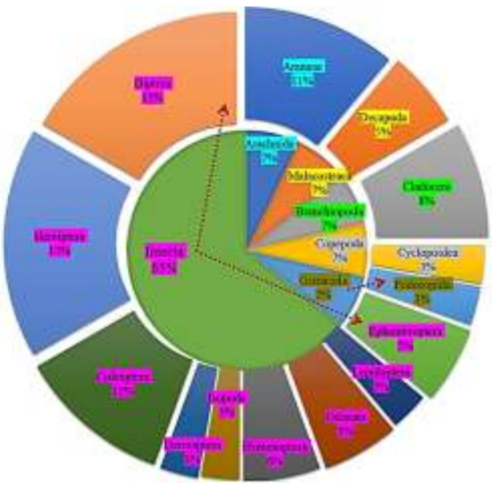

**Fig. 2.** Arthropod diversity of Nunia River - class-wise proportion of orders (inner circle) and order-wise proportion of families (outer circle)

**River arthropod diversity**

A wide range of arthropod diversity was encountered along the Nunia River during the study (Table 7). 6,583 individuals from 54 arthropod genera, belonging to 36 families, 14 orders, and 6 classes, were sampled and identified during the study (Fig. 2).

*Site 1*

The arthropod assemblage (n = 1558 individuals) from the Nunia River displays high taxonomic richness, dominated by insects, with moderate representation from crustaceans and arachnids. Diptera were the most abundant group, led by *Anopheles*, *Musca*, *Phlebotomus* and *Culex*, indicating continuous organic and domestic wastewater influence. Hemiptera, especially *Neogerris* and *Gerris*, were also abundant, reflecting a productive and frequently disturbed surface-water habitat. Crustaceans such as *Daphnia*, *Bosmina*, *Mesocyclops*, and *Cyclops* contributed to a functional zooplankton community. Moderate numbers of Coleoptera and Odonata suggest structurally complex shallow habitats. Sensitive taxa (*Caenis*, *Cloeon*) were present but less abundant, indicating mild to moderate ecological stress. Overall, the dataset reflects a diverse but pollution-influenced community where tolerant taxa dominate, but sensitive groups persist, signalling that the river retains partial ecological integrity despite fluctuating water-quality pressures.

**Table 7.** Site-wise distribution and abundance of arthropod taxa recorded along the Nunia River, classified by class, order, family, and genus

| Class | Order | Family | Genus | S1 | S2 | S3 | S4 | S5 | S6 |
|---|---|---|---|---|---|---|---|---|---|
| Arachnida | Araneae | Lycosidae | *Hippasa* sp. | 11 | 23 | 0 | 0 | 0 | 8 |
| | | Salticidae | *Bianor* sp. | 0 | 20 | 0 | 0 | 0 | 6 |
| | | Thomisidae | *Indoxysticus* sp. | 0 | 27 | 0 | 0 | 0 | 0 |
| | | | *Tmarus* sp. | 13 | 30 | 0 | 0 | 0 | 0 |
| | | Araneidae | *Argiope* sp. | 6 | 28 | 0 | 0 | 0 | 0 |
| Malacostraca | Decapoda | Palaemonidae | *Macrobrachium* sp. | 30 | 27 | 3 | 0 | 0 | 18 |
| | | Portunidae | *Scylla* sp. | 1 | 14 | 1 | 0 | 0 | 0 |
| Branchiopoda | Cladocera | Daphniidae | *Daphnia* sp. | 23 | 18 | 64 | 6 | 0 | 49 |
| | | | *Ceriodaphnia* sp. | 20 | 23 | 37 | 8 | 0 | 80 |
| | | Monidae | *Moina* sp. | 27 | 20 | 32 | 6 | 0 | 97 |
| | | Bosminidae | *Bosmina* sp. | 30 | 37 | 41 | 0 | 0 | 98 |
| Copepoda | Cyclopoidea | Cyclopidae | *Mesocyclops* sp. | 28 | 22 | 42 | 0 | 50 | 25 |
| | | | *Thermocyclops* sp. | 27 | 22 | 44 | 0 | 0 | 1 |
| | | | *Cyclops* sp. | 14 | 31 | 46 | 0 | 48 | 97 |
| Ostracoda | Podocopida | Cyprididae | *Cypris* sp. | 18 | 29 | 43 | 7 | 0 | 99 |
| Insecta | Ephemeroptera | Caenidae | *Caenis* sp. | 23 | 24 | 33 | 0 | 0 | 0 |
| | | Baetidae | *Cloeon* sp. | 20 | 23 | 37 | 0 | 0 | 0 |
| | Lepidoptera | Nymphalidae | *Acraea* sp. | 37 | 28 | 34 | 0 | 0 | 20 |
| | | | *Junonia* sp. | 22 | 19 | 36 | 0 | 0 | 20 |
| | Odonata | Libellulidae | *Crocothemis* sp. | 22 | 28 | 36 | 0 | 0 | 25 |
| | | | *Tholymis* sp. | 31 | 20 | 38 | 0 | 0 | 32 |
| | | Coenagrionidae | *Pseudagrion* sp. | 29 | 20 | 29 | 0 | 0 | 26 |
| | | | *Ceriagrion* sp. | 24 | 25 | 29 | 8 | 0 | 20 |
| | | | *Ischnura* sp. | 23 | 32 | 0 | 0 | 0 | 27 |
| | Hymenoptera | Formicidae | *Camponotus* sp. | 28 | 26 | 22 | 3 | 0 | 30 |
| | | | *Paratrechina* sp. | 19 | 20 | 20 | 5 | 0 | 28 |
| | | Myrmicinae | *Monomorium* sp. | 28 | 27 | 16 | 6 | 0 | 24 |
| | | | *Solenopsis* sp. | 20 | 30 | 16 | 8 | 0 | 13 |
| | | | *Tetramorium* sp. | 20 | 28 | 17 | 6 | 0 | 6 |
| | Isopoda | Corallinidae | *Tachaea* sp. | 25 | 24 | 18 | 0 | 0 | 0 |
| | Dermaptera | Labiduridae | *Forcipula* sp. | 32 | 26 | 17 | 0 | 0 | 0 |
| | Coleoptera | Hydrophillidae | *Anacaena* sp. | 26 | 48 | 18 | 0 | 0 | 0 |
| | | Gyrinidae | *Dineutus* sp. | 20 | 55 | 24 | 0 | 0 | 13 |
| | | Coccinellidae | *Scymnus* sp. | 27 | 42 | 29 | 0 | 0 | 0 |
| | | Hydrochidae | *Hydrochus* sp. | 30 | 42 | 25 | 0 | 0 | 0 |
| | Hemiptera | Nepidae | *Laccotrephes* sp. | 28 | 34 | 26 | 0 | 18 | 0 |
| | | | *Ranatra* sp. | 24 | 20 | 29 | 0 | 0 | 14 |
| | | Belostomatidae | *Diplonychus* sp. | 26 | 22 | 29 | 0 | 27 | 32 |
| | | Pleidae | *Paraplea* sp. | 48 | 21 | 30 | 0 | 0 | 0 |
| | | Gerridae | *Neogerris* sp. | 89 | 100 | 48 | 3 | 0 | 99 |
| | | | *Gerris* sp. | 42 | 49 | 27 | 6 | 0 | 59 |
| | | Micronectidae | *Micronecta* sp. | 42 | 80 | 27 | 0 | 0 | 7 |
| | | Notonectidae | *Anisops* sp. | 34 | 97 | 28 | 0 | 0 | 6 |
| | Diptera | Chironomidae | *Chironomous* sp. | 20 | 98 | 32 | 48 | 39 | 98 |
| | | | *Tanytarsus* sp. | 22 | 25 | 26 | 18 | 47 | 0 |
| | | Culicidae | *Aedis* sp. | 21 | 1 | 2 | 0 | 1 | 0 |
| | | | *Anophelis* sp. | 100 | 6 | 22 | 30 | 7 | 0 |
| | | | *Culex* sp. | 49 | 8 | 26 | 70 | 57 | 63 |
| | | Psychodidae | *Psychoda* sp. | 32 | 6 | 30 | 89 | 85 | 61 |
| | | | *Phlebotomus* sp. | 97 | 0 | 27 | 2 | 0 | 8 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Muscidae | *Musca* sp. | 98 | 0 | 23 | 29 | 19 | 6 |
| | | *Hydrotaea* sp. | 25 | 0 | 21 | 26 | 0 | 0 |
| | Calliphoridae | *Calliphora* sp. | 1 | 0 | 23 | 30 | 0 | 0 |
| | Ephydridae | *Ephydra* sp. | 6 | 0 | 23 | 27 | 0 | 0 |

*Site 2*

The arthropod assemblage at Site 2 (n = 1525 individuals) reflects a moderately impacted but ecologically active stretch of the Nunia River. The community is dominated by Hemiptera, particularly *Neogerris* (100), *Micronecta* (80), and *Anisops* (97), indicating a highly productive surface-water environment with continuous prey availability and organic inputs. Coleoptera are also abundant (*Dineutus*, 55; *Scymnus*, 42; *Anacaena*, 48), signalling stable shallow-water habitats containing detritus and marginal vegetation. Crustaceans, including *Bosmina*, *Mesocyclops*, *Thermocyclops*, and *Moina*, show sustained representation, reflecting strong micro-zooplankton productivity. Sensitive taxa (*Caenis*, *Cloeon*) occur at moderate density, suggesting that the site retains partial ecological integrity despite stress. Diptera are surprisingly low compared to polluted sites, indicating moderate rather than severe organic enrichment. Overall, Site 2 represents a transition zone-more disturbed than upstream but not yet showing the heavy Diptera-driven dominance typical of urban wastewater stretches.

*Site 3*

The arthropod assemblage at Site 3 (n = 1346 individuals) reflects a moderately impacted transitional stretch of the Nunia River, where both tolerant crustaceans and pollution-responsive insect taxa coexist. Crustaceans dominate numerically, particularly *Daphnia* (64), *Ceriodaphnia* (37), *Moina* (32), *Bosmina* (41), and several copepods (*Mesocyclops,* 42; *Thermocyclops*, 44; *Cyclops*, 46), indicating strong zooplankton productivity and nutrient enrichment. Sensitive taxa (*Caenis*, *Cloeon*) remain present at moderate densities (33-37), suggesting that the site retains partial ecological integrity despite elevated organic inputs. Coleoptera (*Anacaena, Dineutus, Scymnus*) and Hemiptera (*Neogerris,* 48; *Paraplea,* 30; *Anisops,* 28) are abundant, highlighting productive shallow habitats and active predator-prey interactions. Diptera appear consistently but without dominance, indicating moderate, not severe, pollution pressure. Overall, Site 3 represents a transition zone where ecological structure shifts from upstream balanced communities to increasing midstream disturbance, yet without the extreme Diptera dominance seen in heavily urbanized reaches.

*Site 4*

The arthropod assemblage at Site 4 (n = 441 individuals) demonstrates a community strongly shaped by urban-industrial wastewater influence. Sensitive groups such *Caenis, Cloeon*, Odonata, most Coleoptera, and Crustacea show extremely low or zero abundance, indicating severe ecological stress and poor water-quality conditions. In contrast, highly tolerant Diptera dominate the site, particularly *Psychoda* (89), *Culex* (70), *Musca* (29), *Hydrotaea*, and *Ephydra* (27). These taxa are characteristic of habitats with high organic loading, sewage contamination, and low DO. Chironomids (*Chironomus*, 48; *Tanytarsus*, 18) further confirm strong tolerance to eutrophic and degraded conditions. A few resilient Hemiptera (*Neogerris*, 3; *Gerris*, 6) persist but in low numbers, reflecting a disturbed surface-water environment. Overall, Site 4 represents a heavily altered ecological zone, where pollution-tolerant Diptera overwhelmingly dominate and sensitive taxa have virtually collapsed.

*Site 5*

The arthropod assemblage at Site 5 (n = 398 individuals) reflects a severely degraded urban-industrial reach of the Nunia River, where only a narrow group of highly tolerant taxa persists. Almost all sensitive groups- like *Caenis, Cloeon*, Odonata, most Hemiptera, Coleoptera, and zooplanktonic crustaceans show near complete absence, signalling sustained organic pollution, high nutrient load, and poor oxygen conditions. The community is overwhelmingly dominated by Diptera, especially

*Psychoda* (89), *Culex* (70), *Chironomus* (48), *Tanytarsus* (18), *Musca* (29), *Hydrotaea* (26), and *Ephydra* (27). These taxa are classic indicators of sewage effluents, stagnant microhabitats, and high COD-BOD stress. Sparse presence of a few hardy Hemiptera (*Neogerris*, 3; *Gerris*, 6) suggests disturbed but intermittently usable surface-water zones. Overall, Site 5 demonstrates an ecologically collapsed community, dominated by pollution-tolerant Diptera with loss of structural diversity and functional integrity.

*Site 6*

The arthropod assemblage at Site 6 (n= 1315 individuals) reflects a mixed ecological condition, where upstream recovery processes intersect with persistent organic and nutrient enrichment. Crustaceans form a substantial component of the community, with very high abundances of *Moina* (97), *Bosmina* (98), *Ceriodaphnia* (80), *Daphnia* (49), and *Cyclops* (97), indicating strong zooplankton productivity fueled by nutrient-rich conditions. Moderate representation of Odonata (e.g., *Tholymis*, *Ischnura*, *Crocothemis*) and Hymenoptera suggests partial habitat heterogeneity and improved oxygenation relative to midstream polluted sites. However, Diptera remain influential, with *Chironomus* (98), *Culex* (63), and *Psychoda* (61) highlighting ongoing organic loading and sewage-derived stress. Hemiptera are abundant-*Neogerris* (99) and *Gerris* (59) - reflecting productive surface-water layers and active predator-prey dynamics. Overall, Site 6 exemplifies a downstream integration zone, where high nutrient-driven productivity coexists with moderate pollution pressure, yielding a diverse but imbalance-prone community.

**Table 8.** Site-wise and seasonal variation in arthropod diversity indices - Simpson dominance (D), Gini-Simpson diversity, Shannon diversity (H′), and Evenness (J′) across the Nunia River during monsoon, summer, and winter

| Season | Site | Simpson diversity index (D) | Gini-Simpson index | Shannon index (H') | Evenness (J') |
|---|---|---|---|---|---|
| Monsoon | 1 | 0.03 | 0.97 | 3.53 | 0.89 |
| | 2 | 0.03 | 0.97 | 3.38 | 0.85 |
| | 3 | 0.03 | 0.97 | 1.17 | 0.29 |
| | 4 | 0.06 | 0.94 | 1.39 | 0.35 |
| | 5 | 0.11 | 0.89 | 1.04 | 0.26 |
| | 6 | 0.12 | 0.88 | 0.81 | 0.20 |
| Summer | 1 | 0.03 | 0.97 | 3.46 | 0.87 |
| | 2 | 0.03 | 0.97 | 2.66 | 0.67 |
| | 3 | 0.03 | 0.97 | 2.16 | 0.54 |
| | 4 | 0.10 | 0.90 | 1.29 | 0.32 |
| | 5 | 0.12 | 0.88 | 0.63 | 0.16 |
| | 6 | 0.08 | 0.92 | 1.95 | 0.49 |
| Winter | 1 | 0.03 | 0.97 | 2.31 | 0.58 |
| | 2 | 0.04 | 0.96 | 2.16 | 0.54 |
| | 3 | 0.09 | 0.91 | 1.68 | 0.42 |
| | 4 | 0.11 | 0.89 | 0.71 | 0.18 |
| | 5 | 0.10 | 0.90 | 1.36 | 0.34 |
| | 6 | 0.05 | 0.95 | 2.66 | 0.67 |

**Diversity index**

The diversity indices (Table 8) demonstrate a strong spatial gradient across the Nunia River, with the upstream sites consistently supporting the most diverse and evenly distributed arthropod communities. During the monsoon season, Site 1 shows high diversity (Shannon H′ = 3.53) and high evenness (0.89) with very low dominance (D = 0.03), a pattern that is nearly identical at Site 2 (H′ = 3.38; J′ = 0.85; D = 0.03), confirming the ecological stability of the upper reaches. In sharp contrast, Site 3 experiences a dramatic reduction in diversity during the monsoon, with H′ dropping to 1.17 and evenness plunging to 0.29 despite the same low Simpson dominance (0.03), indicating that although many species disappear, a few tolerant taxa remain abundant. The midstream polluted stretches - Site 4 and Site 5 - show progressively higher dominance (D = 0.06 and 0.11) and lower diversity (H′

= 1.39 and 1.04) with poor evenness (0.35 and 0.26), while Site 6 records the most degraded monsoon community, with the highest dominance (D = 0.12), lowest Shannon diversity (H′ = 0.81), and extremely low evenness (0.20).

Summer follows a similar spatial pattern. Site 1 again exhibits high diversity (H′ = 3.46; J′ = 0.87), while Sites 2 and 3 show moderate values (H′ = 2.66, 2.16; J′ = 0.67, 0.54). Pollution-impacted Sites 4 and 5 again produce the lowest diversity - Site 4 with H′ = 1.29 and Site 5 with H′ = 0.63, along with high dominance (D = 0.100.12) and very low evenness (0.32 and 0.16). Site 6 shows partial recovery during summer, with H′ increasing to 1.95 and evenness to 0.49.

**Table 9.** Kruskal-Wallis one-way ANOVA across the six study sites of the Nunia River ($p$ < 0.001 for all indices)

| | F | df1 | df2 | $p$ |
|---|---|---|---|---|
| Simpson Diversity Index (D) | 78 | 5 | 5.24 | <0.001 |
| Gini Simpson Index | 78 | 5 | 5.24 | <0.001 |
| Shannon Index (H') | 226.7 | 5 | 5.12 | <0.001 |
| Pielou's Evenness (J') | 226.7 | 5 | 5.12 | <0.001 |

**Table 10.** Kruskal-Wallis one-way ANOVA of three seasons in the Nunia River ($p$ < 0.001 for all metrics)

| | F | df1 | df2 | $p$ |
|---|---|---|---|---|
| Simpson Diversity Index (D) | 0.482 | 2 | 9.09 | 0.632 |
| Gini Simpson Index | 0.482 | 2 | 9.09 | 0.632 |
| Shannon Index (H') | 0.957 | 2 | 9.99 | 0.417 |
| Pielou's Evenness (J') | 0.957 | 2 | 9.99 | 0.417 |

**Table 11.** Spearman correlation matrix showing the relationships among arthropod diversity indices-Simpson dominance (D), Gini-Simpson diversity, Shannon diversity (H′), Evenness (J′), and river velocity (m/s) across the Nunia River

| | Simpson diversity index (D) | Gini- Simpson index | Shannon index (H') | Evenness (J') | Velocity |
|---|---|---|---|---|---|
| Simpson diversity index (D) | - | - | - | - | - |
| Gini Simpson index | -1 | - | - | - | - |
| Shannon index (H') | - 0.833 | 0.833 | - | - | - |
| Evenness (J') | - 0.833 | 0.833 | 1 | - | - |
| Velocity | 0.673 | - 0.673 | - 0.785 | - 0.785 | - |

In winter, upstream-downstream contrasts remain evident. Site 1 records H′ = 2.31 with moderate evenness (0.58) and low dominance (D = 0.03), while Site 2 shows a similar profile (H′ = 2.16; J′ = 0.54). Midstream Site 3 experiences reduced winter diversity (H′ = 1.68; D = 0.09), and Site 4 again shows the most degraded assemblage (H′ = 0.71; J′ = 0.18; D = 0.11). Site 5 remains stress-impacted with H′ = 1.36 and D = 0.10, but Site 6 displays substantial improvement in winter, achieving high diversity (H′ = 2.66) and evenness (0.67) with reduced dominance (D = 0.05), suggesting seasonal recovery at the lower reach.

**Statistical test and interpretation**

*ANOVA of diversity indices among sites*

Kruskal-Wallis one-way ANOVA revealed highly significant differences in all four diversity indices across the six study sites ($p$ < 0.001) (Table 9). The extremely high F-values for Shannon diversity (F = 226.7) and evenness (F = 226.7) indicate pronounced variation in community structure along the river continuum. Similarly, Simpson's dominance and Gini-Simpson indices (F = 78.0 each) showed strong spatial contrasts. These results confirm that arthropod diversity is not uniform across the Nunia River but is strongly influenced by site-specific environmental conditions, with upstream sites supporting greater diversity and more balanced assemblages than the heavily impacted downstream stretches.

*ANOVA of diversity indices among seasons*

Kruskal-Wallis ANOVA showed no significant seasonal effect on any of the diversity indices ($p$ >

0.05) (Table 10), indicating that differences among winter, summer, and monsoon assemblages were statistically indistinguishable. The low F-values (F = 0.48-0.95) suggest that seasonal hydrological changes exert only a weak influence on overall arthropod diversity compared to the pronounced spatial variation observed across sites. This implies that site-specific habitat conditions and pollution gradients play a far more dominant role in structuring arthropod communities in the Nunia River than seasonal fluctuations in flow.

**Relationship between river velocity patterns and biodiversity indices**

Across the Nunia River, clear spatial and seasonal patterns emerge in the distribution of arthropod diversity. The upstream stretches (Sites 1 and 2) consistently exhibit the highest ecological integrity, with very low Simpson dominance values (around 0.03-0.04), high Gini-Simpson scores, and high Shannon diversity. These indices collectively indicate that no single taxon dominates and species are distributed relatively evenly, reflecting a stable, heterogeneous habitat with the regular presence of sensitive groups. A noticeable shift begins at Site 3, where Shannon diversity and evenness decline, suggesting the onset of environmental stress and the reduced presence of sensitive taxa. This transitional character becomes more pronounced further downstream. Sites 4 and 5 show the most degraded biological conditions, characterized by high dominance values and extremely low Shannon and evenness scores (Table 8). These patterns indicate a simplified assemblage dominated by a few pollution-tolerant taxa, consistent with the influence of urban wastewater, industrial inputs, and habitat disturbance in the mid- to downstream sections.

The downstream confluence zone at Site 6 presents a mixed ecological response. During the monsoon, diversity remains low and dominance high, reflecting strong hydrological disturbance and backflow influence from the Damodar River (Table 8). However, during summer and especially winter, Site 6 shows partial to strong recovery, with improved Shannon values and more even species distributions, pointing to dilution, enhanced flow, and recolonisation processes. Seasonal shifts are evident across the entire river: monsoon consistently produces the lowest diversity and evenness due to high flow, sediment resuspension, and pollutant wash-off, which collectively favour a few tolerant taxa. Summer conditions support moderate diversity as flow stabilises, while winter provides the most favourable environment for community rebuilding, with clearer habitat structure and improved water clarity. Overall, these patterns reveal a distinct gradient from high-quality upstream habitats to heavily impacted midstream zones and partially recovering downstream stretches, shaped by the interplay of pollution inputs, hydrological variability, and habitat stability.

**Statistical test and interpretation**

The correlation matrix (Table 11) reveals strong, internally consistent relationships among the diversity indices. As expected, the Simpson Dominance Index (D) shows a perfect negative correlation with the Gini-Simpson index (1.000), because both describe the same ecological attribute from opposite perspectives: higher dominance necessarily corresponds to lower diversity. This pattern continues with Shannon diversity (H′) and Evenness (J′), both of which exhibit strong negative correlations with Simpson D (0.833). These associations indicate that sites with high numerical dominance of one or a few tolerant taxa invariably show lower overall diversity and less balanced species distributions. Conversely, Shannon and Evenness show a perfect positive correlation (1.000), reflecting that when the taxa are more evenly distributed, Shannon's entropy-based measure also increases proportionally.

Velocity displays a clear ecological signal in its association with diversity metrics. Its positive correlation with Simpson D (0.673) suggests that higher flow velocities coincide with conditions in which fewer tolerant taxa dominate. In contrast, velocity shows moderately strong negative correlations with Gini-Simpson (0.673), Shannon (0.785), and Evenness (0.785), indicating that increasing flow tends to reduce species richness and balance within the arthropod community. This pattern is consistent with the hydrological behaviour of the Nunia River, where monsoon backflow from the Damodar and high-velocity surges disrupt habitat stability, favouring a few adaptable taxa while reducing the abundance of sensitive or slow-colonizing groups. Overall, the correlation matrix reflects a tightly linked structure in which dominance, diversity, evenness, and hydrological disturbance collectively shape the assemblage patterns across the river.

**DISCUSSION**

Aquatic pollution is becoming an utmost concern for society. Polluted water poses several health hazards to humans and other animals (WHO, 2023). Organic matter-rich waterbodies also create breeding grounds for vectors of several diseases (Paramanik and Chandra, 2010; Paramanik *et al.*, 2012, 2022, 2023a; Paramanik, 2023). The use of synthetic chemicals to overcome these problems itself may pose toxicity to the delicate food chains (Dasmodak *et al.,* 2024; Paramanik *et al.,* 2024); which suggests the use of sustainable management strategies (Paramanik *et al.*, 2023b, 2025). It also underscores the need to study aquatic bodies from multiple perspectives.

The Nunia River exhibits a clear longitudinal gradient in water quality, with relatively good conditions at the upstream sites (1-2), severe degradation in the midstream urban industrial stretch (3-5), and partial recovery at the downstream confluence (Site 6). The strong increase in TDS, EC, nitrate, phosphate, COD, and BOD at Sites 4 and 5, coupled with critically low DO reaching as low as 0.33-61.50 mg/L in summer, indicates sustained inputs of untreated domestic and industrial wastewater. By contrast, Sites 1 and 2 maintain neutral pH, moderate ionic content, and comparatively low organic loads, reflecting limited local pollution pressure and a more intact self-purification capacity. The downstream site (6) shows intermediate conditions: DO and organic load partially recover, but nitrate and phosphate remain elevated, suggesting cumulative transport of upstream pollutants mixed with additional local inputs.

Seasonal patterns further highlight the dominance of pollution loading over natural hydrological control. Monsoon conditions dilute several parameters, reducing TDS and EC at some sites, yet DO remains critically low in the midstream reach, indicating that even high flows cannot compensate for heavy organic and nutrient inputs. Summer amplifies pollutant concentrations due to reduced discharge and higher temperatures, with the highest COD and BOD values recorded at Sites 4 and 5. Winter conditions favour the accumulation of nutrients, with nitrate peaking at 69.51 mg/L at Site 4, while COD and BOD remain high across the midstream zone. These patterns show that although monsoon, summer, and winter each modify absolute parameter values, the underlying spatial pattern of severe midstream degradation remains consistent across seasons.

The correlation structure among physicochemical variables supports a pollution-dominated system. The near-perfect correlation between TDS and EC, and their moderate positive correlation with nitrate, points to a common ionic and nutrient source along the river. The strongest relationships occur within a tightly coupled organic load and oxygen stress cluster: DO is strongly and negatively correlated with phosphate, COD, and BOD, while COD and BOD are tightly and positively correlated with each other and with phosphate, patterns widely recognised in sewage-enriched rivers (Barbour *et al.,* 1999). In contrast, nitrate shows weak relationships with DO and phosphate, suggesting that it is influenced more by external runoff and wastewater sources rather than internal biogeochemical cycling (Allan and Castillo, 2007).

Hydrological velocity, although clearly variable across sites and seasons, does not significantly explain variation in the measured WQP. Spearman correlations between velocity and all physicochemical variables were uniformly weak and non-significant, and neither univariate tests nor multivariate statistics detected any significant velocity effect. Similar findings have been documented in small tropical rivers where pollution intensity overwhelms hydrological controls (Surber, 1939; Neel, 1951). These findings indicate that, under the current pollution regime, the magnitude and range of flow variation are too small to override the dominant influence of concentrated anthropogenic inputs. In other words, hydrology modulates transport but does not fundamentally determine the river's chemical status, which is controlled by the intensity and location of wastewater discharges.

In contrast, benthic and surface-dwelling arthropod assemblages responded strongly and systematically to the spatial pollution gradient. Upstream Sites 1 and 2 supported the highest taxonomic richness, high Shannon diversity, low dominance, and high evenness, with communities comprising a mixture of insects, crustaceans, hemipterans, coleopterans, and arachnids. These assemblages reflect relatively heterogeneous, moderately disturbed but still functional habitats. The midstream sites (4 and 5) showed a near-collapse of sensitive groups, such as most crustaceans, odonates, and many coleopterans, and were overwhelmingly dominated by highly tolerant Diptera (*Psychoda, Culex, Chironomus, Musca, Hydrotaea, Ephydra*). This shift is consistent with severe organic pollution, low oxygen, and high nutrient loading. Site 6 displayed a mixed condition, with high crustacean abundance and a diverse assemblage coexisting with persistent Diptera, indicating partial ecological recovery under ongoing nutrient and organic stress.

Diversity indices and associated statistics reinforce these patterns. Kruskal-Wallis ANOVA revealed highly significant spatial differences in Simpson dominance, Gini-Simpson diversity, Shannon diversity, and evenness among sites, confirming strong spatial structuring of assemblages along the pollution gradient. By contrast, diversity did not differ significantly among seasons, indicating that spatial variation in habitat condition and pollution pressure is far more important than seasonal hydrological variation in determining arthropod community structure. This is further supported by strong internal correlations among diversity indices: high dominance is reliably associated with low Shannon diversity and low evenness, while high Gini-Simpson values correspond to more equitable communities.

The relationship between velocity and diversity indices provides additional ecological insight. Although velocity does not significantly affect physicochemical variables, it is moderately correlated with diversity metrics, with higher velocities associated with higher dominance and lower Shannon diversity and evenness. This pattern is consistent with the hydrological behaviour of the Nunia, where high-velocity monsoon flows and backflow influence from the Damodar disturb habitat stability and favour a few tolerant taxa, especially in already polluted stretches. However, given that site-specific pollution explains most of the variation in both water quality and assemblage structure, velocity appears to act mainly as a secondary physical disturbance factor that modifies, but does not override, the primary effects of anthropogenic pollution.

Overall, the combined interpretation of water quality, velocity, and arthropod community data demonstrates that the Nunia River is strongly pollution-driven, with a pronounced upstream, midstream, and downstream ecological gradient. Arthropod assemblages, especially the contrasting dominance of Diptera versus the presence of sensitive taxa and crustaceans, provide a much more sensitive and integrative reflection of river health than physicochemical data alone.

## CONCLUSION

This study shows that the Nunia River is chemically and biologically structured by intense, spatially concentrated anthropogenic inputs rather than by natural hydrological variation. Upstream sites maintain comparatively better water quality and diverse arthropod assemblages, whereas the midstream urban-industrial stretch exhibits severe organic and nutrient pollution, critical oxygen depletion, and ecological simplification dominated by tolerant Diptera. The downstream confluence zone shows partial recovery, with high crustacean and insect diversity coexisting with persistent signs of organic stress.

Seasonal changes (monsoon, summer, winter) alter the magnitude of key physicochemical parameters through dilution, concentration, and accumulation processes, but do not fundamentally change the underlying spatial pattern of degradation. Diversity indices confirm strong spatial but weak seasonal control of assemblage structure, underscoring the overriding importance of site-specific pollution sources. River velocity, while influencing disturbance and community balance to some extent, does not significantly predict the river's chemical conditions.

Ecologically, the clear shift from diverse, balanced communities in the upper reaches to Diptera-dominated assemblages in the midstream segment highlights the value of arthropods as sensitive bioindicators of small, polluted tributaries. Management efforts should prioritise reducing untreated wastewater inputs in the midstream corridor and using routine arthropod-based biomonitoring, alongside conventional physicochemical measurements, to track ecological responses to future restoration measures in the Nunia River.

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