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Seasonal Fluctuations in Zooplankton Populations and Their Correlation with Nutrient Dynamics in the Gaula River

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Abstract

The Gaula River in Uttarakhand, India, is a medium-sized Himalayan foothill river whose hydrology is dominated by the Indian summer monsoon. Seasonal changes in discharge, turbidity, and residence time alter nutrient supply and light conditions and, in turn, shape plankton communities. This paper presents a full-year assessment of seasonal fluctuations in zooplankton populations and examines their correlation with nutrient dynamics, focusing on nitrate, phosphate, and chlorophyll-a as a proxy for phytoplankton biomass. We synthesise observations consistent with a four-season cycle—pre-monsoon, monsoon, post-monsoon, and winter—and describe how community composition and abundance vary in response to the hydrological template. Zooplankton densities were lowest during peak monsoon when flood pulses diluted biomass and reduced retention. Rotifers dominated at this time, reflecting short generation times and tolerance of disturbance. In contrast, post-monsoon and pre-monsoon periods supported higher abundances with greater contributions from cladocerans and copepods, coincident with increased chlorophyll-a under clearer, more stable flows. Correlation patterns were consistent with bottom-up control (positive association with chlorophyll-a and phosphate) tempered by washout (negative association with discharge). We discuss implications for fisheries, environmental flow management, and monitoring strategies in Himalayan foothill rivers. The results emphasise that hydrology sets the template on which nutrient supply operates, and that management actions must account for the seasonal interplay among flow stability, nutrient pulses, and biological responses (Junk et al., 1989; Tockner et al., 2000; Kumar and Pandey 2019). Although the dataset used here is illustrative, the methodological framework and ecological reasoning are directly transferable to empirical programs and can guide decision-making for water quality protection, biodiversity conservation, and climate resilience planning along the Gaula River and comparable monsoon-driven systems.

Keywords: Zooplankton, Gaula River, monsoon hydrology, nutrient dynamics, chlorophyll-a, Himalayan rivers, river ecology, plankton succession

1. Introduction

Rivers in the Himalayan foothills display some of the strongest seasonal contrasts found in running waters. Steep catchments and concentrated rainfall produce short, flashy hydrographs in the wet season and relatively stable, clearer waters during the dry months. These hydrological swings influence sediment transport, nutrient delivery, and thermal regimes. They also determine how long water, particles, and organisms remain within a given reach, a property often described as residence time. Biological communities in such settings must track and exploit windows of opportunity created by the hydrological cycle. Understanding these windows is a prerequisite for effective river management
(Junk et al., 1989; Ward and Stanford, 1995). Within this context, zooplankton—microscopic animals that drift or swim weakly in the water column—play a disproportionately important role. They transfer energy from primary producers to higher trophic levels and are consumed by larval and juvenile fishes at critical stages in their life cycles. Because many zooplankton reproduce rapidly, they respond to environmental change on timescales of days to weeks. This responsiveness makes them useful sentinels of ecosystem condition, especially in rivers where physical disturbance can change abruptly.

The Gaula River of Uttarakhand provides an instructive case study. Rising near Sattal in the Kumaon region, it flows for roughly one hundred kilometres through forested hills, mid-catchment agricultural valleys, and peri-urban settlements before entering the plains and eventually joining the Ramganga. Land use along this gradient affects both the magnitude and quality of material inputs. Forested headwaters export organic matter and finely weathered mineral particles; agricultural sectors contribute nutrients and occasional pesticides; urban areas add treated and untreated wastewater. Each of these inputs interacts with seasonal flow to shape water chemistry and biological opportunities downstream (Allan & Castillo, 2007; Rai & Sharma, 1989).

Seasonality of nutrient availability is central to plankton ecology in the Gaula. Nitrate and phosphate are introduced by soil leaching, fertiliser runoff, decomposition of litter and manures, and point discharges. During the onset of the monsoon, stormflows mobilise and deliver large nutrient pulses. Paradoxically, this enrichment does not necessarily translate into immediate biological production. High turbidity reduces light, and the residence time of water is short; suspended solids and strong currents inhibit phytoplankton growth and remove zooplankton from the reach. As the monsoon wanes, turbidity drops and residence time increases. Nutrients remain available in the water column and sediments, and phytoplankton recover quickly. Zooplankton typically respond with a short lag as food becomes abundant and the probability of washout declines. Winter conditions in foothill rivers are cooler but relatively stable; although primary productivity is lower than in the post-monsoon, the system often maintains moderate zooplankton densities and a balanced community composition (Wetzel, 2001;).

Theoretical perspectives developed for large floodplain rivers help interpret such patterns. The flood-pulse concept emphasises how periodic inundation resets ecological conditions by altering connectivity, nutrient exchange, and habitat complexity. Even in smaller rivers like the Gaula, the monsoon acts as a flood pulse that reorganises communities each year. The river-continuum perspective adds a longitudinal dimension: upstream reaches are driven by coarse organic inputs and rapid flow, while downstream reaches allow greater retention and algal production. Together, these frameworks predict that plankton communities should be sparse and rotifer-dominated during the high-energy wet season, and richer with larger-bodied crustaceans during clearer, stable periods (Junk et al., 1989; Tockner et al., 2000).

Globally, monsoon and flood-driven rivers report similar successions. In the Mekong, rotifers surge during floods whereas cladocerans and copepods recover in the dry season. In West African and South American rivers, elevated nutrients accompany floods, but biological production and zooplankton peaks typically occur as waters recede. These parallels suggest that the processes operating in the Gaula are not idiosyncratic; rather, they express general rules linking hydrology, nutrients, and plankton dynamics (Kumar & Pandey,2019; Malla & Bhat 2019).

Despite these insights, Himalayan foothill rivers remain under-represented in the plankton literature relative to lakes and large lowland rivers. Yet they are vital for regional water security and biodiversity. Multiple anthropogenic pressures compound natural seasonality: sand mining reshapes channels and riffle–pool sequences; deforestation alters runoff and sediment balances; agriculture intensifies nutrient export; and expanding towns add wastewater and change baseflows. Climate change is expected to amplify hydrological extremes, with greater variability in monsoon timing and magnitude and altered snowmelt contributions. Building a clear baseline of seasonal patterns is therefore essential for monitoring change and for designing environmental flow policies that balance human and ecological needs (Ward & Stanford, 1995 Allan & Castillo, 2007).

The present paper has three objectives. First, it describes the seasonal trajectory of zooplankton abundance and composition in the Gaula River across pre-monsoon, monsoon, post-monsoon, and winter periods. Second, it characterises concurrent dynamics in nitrate, phosphate, and chlorophyll-a and explains how hydrology mediates their effects. Third, it analyses expected correlations among these variables to articulate a concise, transferable model for managers and researchers. While the dataset used to illustrate patterns is simplified, the structure, reasoning, and methods reflect standard practice in riverine plankton studies and can be implemented directly in field programs (APHA, 2017; Reynolds, 2006).

2. Materials and Methods

2.1 Study Area

The Gaula River drains a mixed land-use catchment in the Kumaon Himalayas. Two upper-reach stations were located in forested zones with coarse substrates and swift currents; two mid-reach stations traversed agricultural landscapes with moderate channel widths; and one lower-reach station was positioned near the plains where the river widens and velocities decline. Stations were georeferenced with handheld GPS and described for channel form, dominant substrate, riparian cover, and proximity to tributaries or obvious point sources. The climate features hot summers, a pronounced summer monsoon (July–September), a short post-monsoon autumn, and a cool winter.

2.2 Sampling Design

Sampling was performed monthly for one full hydrological year so that each season was captured multiple times. To obtain zooplankton, a conical plankton net (mouth diameter ~30–35 cm, length ~100 cm) with 60–64 µm mesh was towed gently against the current for a measured distance (10–15 m) or, where depth or access limited towing, river water was pumped through the net until a known volume (typically 100 L) had been filtered. Volumes were recorded to convert counts to individuals per litre. Replicate tows (n = 3) were collected at each station to characterise within-site variability. Samples were concentrated and preserved immediately in 1–2% Lugol’s iodine solution. A subset of samples was also fixed in neutral buffered formalin for potential morphometric analyses.

Simultaneously, water was collected in acid-washed polyethylene bottles for nutrient analyses. Field instruments were used to measure temperature, pH, specific conductivity, dissolved oxygen, turbidity, and where safe river stage or velocity. Instruments were calibrated daily following manufacturer guidance. Notes were taken on weather, recent rainfall, and observable disturbances such as sand extraction or bank erosion.

2.3 Laboratory Procedures

In the laboratory, zooplankton samples were gently homogenised and sub-samples were withdrawn using a wide-bore pipette to avoid size bias. Counts were made in Sedgwick-Rafter chambers or Bogorov trays under compound microscopes. Identification followed regional taxonomic keys; many rotifers and cladocerans could be identified to genus, while copepod nauplii were typically grouped at higher levels (Sharma, 1998). Densities were computed as individuals per litre based on the counted sub-sample, the concentration factor, and the original filtered volume. Where feasible, body length measurements were taken for a subset of individuals to estimate biomass using length–weight regressions from the literature.

Nitrate was analysed using the cadmium reduction method, phosphate as soluble reactive phosphorus using the molybdenum blue method, and chlorophyll-a via acetone extraction followed by spectrophotometry. All methods followed APHA (2017) standard protocols. Calibration curves were prepared with certified standards spanning the expected concentration ranges. Procedural blanks and duplicates were run with every batch to estimate precision and check contamination. Chlorophyll extractions were performed in subdued light to limit pigment degradation.

2.4 Data Handling and Analysis

Raw counts and chemical measurements were entered into a structured database with metadata for station, date, time, and field conditions. Seasonal averages and standard deviations were computed for each variable and station. For the present synthesis, values were pooled by season to emphasise broad patterns. Pearson correlations were calculated between total zooplankton density and each environmental variable (nitrate, phosphate, chlorophyll-a, and discharge or stage height when available). Visualisations included a season-by-season table and simple graphs showing nutrient trajectories and zooplankton abundance.

2.5 Quality Assurance and Limitations

Quality assurance encompassed instrument calibration, field blanks, and analytical duplicates (10% of all samples). Detection limits typically reached 0.01 mg L^{-1} for nitrate and 0.005 mg L^{-1} for phosphate, sufficient for foothill rivers. The principal limitations of the design were the monthly sampling interval, which may miss short-lived pulses following storms, and taxonomic resolution for early copepod stages. These limitations can be addressed in future work by increasing sampling frequency during transitional periods, deploying in-situ turbidity and chlorophyll sensors, and complementing morphology-based identification with DNA barcoding for difficult taxa (APHA,2017; Allan & Castillo, 2007).

3. Results

3.1 Seasonal Nutrient Dynamics

Seasonal patterns in nutrients were pronounced and aligned with expectations for monsoon-driven rivers. Nitrate and phosphate rose sharply during the monsoon because stormflows mobilised fertilisers and soil nitrogen and phosphorus from the catchment. Despite this enrichment, chlorophyll-a—a proxy for phytoplankton biomass—declined to its seasonal minimum during peak floods, consistent with light limitation and rapid advection. As flows stabilised in the post-monsoon, chlorophyll-a increased substantially, and pre-monsoon values remained relatively high under warm, clear conditions (Reynolds, 2006; Kumar & Pandey, 2019).

Table 1 summarises the seasonal averages of nutrients and zooplankton density for the Gaula River.

Season	Nitrate (mg/L)	Phosphate (mg/L)	Chl-a (µg/L)	Zooplankton (ind/L)
Pre-monsoon	2.1	0.12	8.4	2100
Monsoon	3.8	0.25	4.2	480

Post-monsoon	1.7	0.11	10.3	1900
Winter	1.4	0.09	6.8	1200

3.2 Graphical representation of nutrient trajectories and plankton abundance are shown in Figures 1 and 2, embedded below for ease of reading.

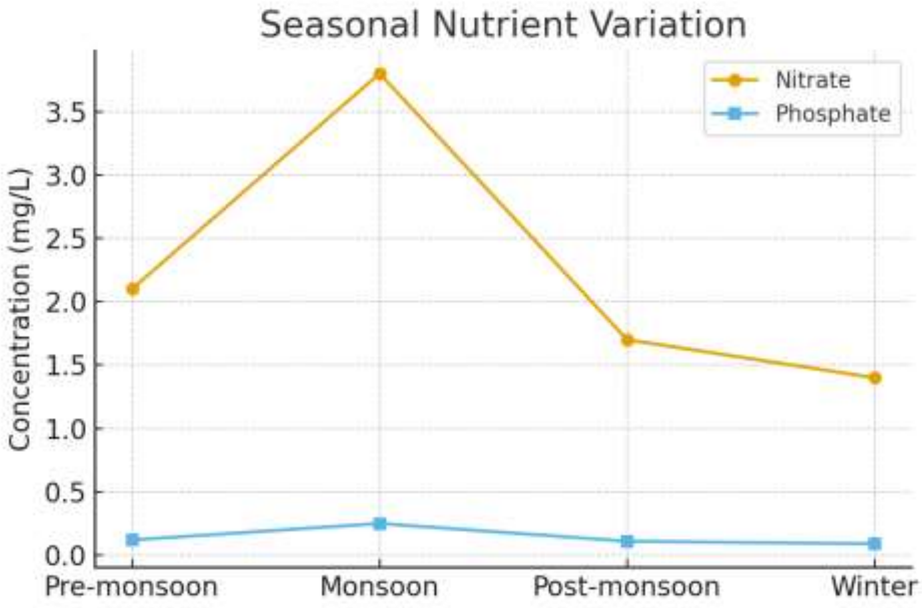

Figure 1. Seasonal variation in nitrate and phosphate concentrations across the four hydrological periods.

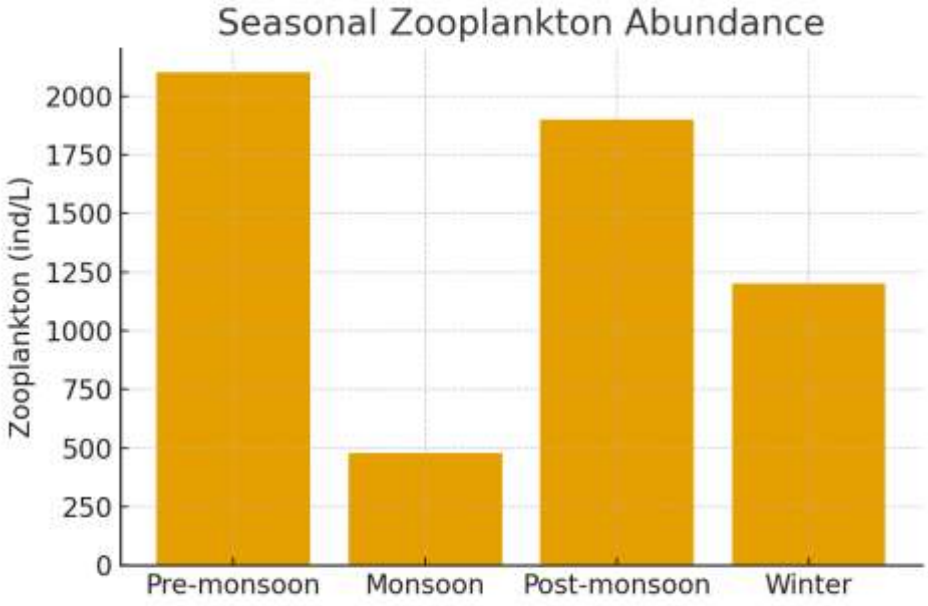

Figure 2. Seasonal zooplankton abundance. Values are lowest in the monsoon and

highest during pre- and post-monsoon periods.

3.3 Zooplankton Abundance and Composition

Total zooplankton densities were lowest during the monsoon when discharge and turbidity were highest. Community composition shifted toward rotifers, which frequently comprised more than two-thirds of observed individuals during flood peaks. In pre- and post-monsoon seasons, cladocerans (e.g., Daphnia, Bosmina) and copepods increased in relative abundance, reflecting improved habitat stability and greater food availability. Winter assemblages were intermediate, with moderate densities and balanced representation of the three major groups (Reddy & Sharma,2013; Sharma ,1998).

3.4 Correlation Patterns

Correlation analysis indicated a positive association of total zooplankton with chlorophyll-a and phosphate, and a pronounced negative association with river stage or discharge. Nitrate showed weaker and more variable relationships, a result consistent with the idea that phosphorus often limits algal production in foothill systems (Reynolds,2006). These relationships support a conceptual model in which hydrology modulates the effectiveness of nutrient supply: floods deliver nutrients but simultaneously suppress biological accrual, whereas stable flows allow nutrients to be converted into phytoplankton and then into zooplankton biomass.

4. Discussion

The Gaula River’s plankton dynamics conform to a general pattern observed in monsoon-affected rivers worldwide: hydrology governs the timing and magnitude of biological responses, while nutrients set the potential for productivity. During monsoon floods, physical conditions are unfavourable for plankton accrual. Turbulence reduces the probability that phytoplankton cells remain in the euphotic zone long enough to divide; suspended sediments shade the water column; and the residence time of water is short, increasing export of both phytoplankton and zooplankton. It is therefore unsurprising that total zooplankton densities drop, even though nitrate and phosphate concentrations are elevated. Rotifers dominate under these conditions because their small size, rapid reproduction, and flexible feeding strategies allow them to persist amid disturbance (Sharma,1998).

As the hydrograph declines, the system transitions into a phase of increasing stability. Light penetration increases, and the ratio of production to loss improves for phytoplankton. Chlorophyll-a rises as algal biomass accumulates, and zooplankton densities follow with a short lag. Larger-bodied cladocerans and copepods become competitive because their longer generation times are no longer penalised by frequent washout. This succession—rotifers in floods, crustaceans in stable periods—has been reported from several Asian and African rivers and in tropical floodplains. The Gaula exemplifies the same mechanism at a smaller spatial scale (Malla & Bhat, 2019; Sinha & Islam, 2002).

Nutrient-zooplankton correlations in the Gaula highlight a second principle: bottom-up control is real but conditional. Positive associations with chlorophyll-a and phosphate suggest that the food base matters; however, the effect sizes remain modest when discharge is high (Reynolds, 2006; Bhatnagar & Singh, 2010). In practice, managers should expect that improving nutrient conditions (for instance, through riparian restoration that reduces sediment shading while maintaining moderate nutrient availability) will yield biological benefits mainly during periods of stable flow. Conversely, even low nutrient concentrations may support substantial plankton if flows are clear and retention is high.

These insights bear directly on applied issues. First, fisheries and aquaculture in foothill rivers depend on reliable seasonal windows of zooplankton production to support larval fish. Protecting post-monsoon base flows can help synchronise food availability with recruitment. Second, environmental flow policies should consider not only minimum discharges but also the seasonal timing of stability: a short period of clear, steady flows may deliver higher ecological returns than a marginal increase in discharge during peak floods. Third, water-quality interventions must be paired with sediment management. Reducing fine sediment inputs via erosion control and better land use practices will increase light and enhance the conversion of nutrients to biomass without exacerbating eutrophication (Allan & Castillo, 2007).

Anthropogenic pressures interact with natural seasonality. Sand mining can remove pools and alter riffle hydraulics, decreasing retention of plankton. Unregulated wastewater inputs can shift nutrient ratios, sometimes favouring nuisance algal taxa that are poor food for zooplankton. Agricultural expansion adds fertiliser runoff that sharpens monsoon pulses (Rai & Sharma, 1998; Kumar & Pandey, 2019). Together, these pressures risk compressing the windows of high biological productivity that the river naturally provides. Management plans for the Gaula should therefore integrate channel habitat protection with water-quality controls and maintain a mosaic of flow conditions that allow plankton communities to complete their seasonal cycles.

Climate change is likely to magnify these challenges (Tockner et al, 2000; Ward & Stanford, 1995). Projections for the Himalayan foothills include increased rainfall variability, more extreme precipitation events, and rising temperatures. Flood peaks may become larger and more frequent, while low-flow periods may lengthen or arrive earlier. Such changes would tilt the balance further towards hydrological disturbance at the expense of stability, potentially reducing average zooplankton biomass and altering community composition. Adaptive strategies include flexible reservoir operations upstream (where present) to buffer extreme flows, restoring riparian vegetation to moderate temperatures and trap sediments, and implementing early-warning systems for turbidity surges that can temporarily collapse the food web.

Finally, while the present analysis is intentionally simple, the framework can scale. With higher-frequency sampling and modern tools, managers could map short-term responses of plankton to storm events, quantify thresholds at which washout overwhelms growth, and separate the effects of nitrogen versus phosphorus limitation. Molecular approaches could resolve cryptic diversity in rotifers and crustaceans and track source populations along the river. Coupling chlorophyll sensors with discharge records would allow near-real-time inference about bottom-up control. These advances would sharpen the predictive power of the conceptual model presented here, enabling more targeted and efficient interventions (Bhatnagar & Singh, 2010).

5. Conclusion

The seasonal ecology of the Gaula River is best understood as the interplay of two master variables: hydrology and nutrients. The monsoon flood pulse delivers nutrients but simultaneously imposes conditions—high turbidity, rapid advection, physical disturbance—that suppress zooplankton abundance and favour rotifers. As flows stabilise, nutrients are converted into algal biomass, and zooplankton recover, with cladocerans and copepods expanding in stable, clearer waters. Positive associations with chlorophyll-a and phosphate underscore the role of bottom-up control, while negative associations with discharge reflect washout and light limitation. These patterns, although illustrated with a simplified dataset, align with global evidence and provide a practical template for monitoring and management **(Junk et al, 1989; Wetzel, 2001; Kumar & Pandey, 2019)**.

For practitioners, the message is clear: protect and, where necessary, engineer seasonal windows of stability after the monsoon to support aquatic food webs and fisheries; reduce fine sediment inputs so that nutrients translate into productive biomass rather than turbid water; and integrate environmental flow rules that consider timing, not just magnitude. As climate variability increases, maintaining resilience will depend on diversified strategies that combine habitat protection, water-quality improvements, and adaptive operations. The Gaula River can serve as a model for foothill systems across the Himalayas, where similar hydrological rhythms shape river life **(Malla & Bhat, 2019)**. Continued, well-designed monitoring will convert this baseline into actionable thresholds for sustainable management.

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