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Ecological Modeling of Aquatic Insect Contributions to Buffering Capacity in a Tropical Tidal River, Nigeria

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ABSTRACT

The buffering capacity of tropical tidal rivers is critical for sustaining aquatic life by maintaining chemical balance, yet the role of aquatic insects in this process remains underexplored. This study aimed to model and quantify the effect of aquatic insect communities on the buffering capacity of the Calabar River, Nigeria. Seasonal field sampling captured aquatic insect abundance, diversity, and water quality parameters at upstream, midstream, and downstream stations. Laboratory incubation experiments compared buffering capacity changes over 72 hours in microcosms with and without aquatic insects. A dynamic model simulated the influence of insect density on buffering dynamics. Results revealed that insect abundance peaked in the wet season, reaching 915 ± 42 individuals/m² downstream, with Shannon diversity indices up to 3.00. Buffering capacity ranged from 108 ± 6 mg/L $CaCO_3$ in the dry season midstream to 130 ± 7 mg/L $CaCO_3$ downstream in the wet season. Incubations showed an 18.2% increase in buffering capacity with insects present, significantly higher than the 4.5% change in controls ($P< 0.001$). The model confirmed that higher insect densities corresponded to greater buffering enhancements. Field data demonstrated a strong positive correlation ($r= 0.72$, $P= 0.001$) between insect abundance and buffering capacity. These findings indicate that aquatic insects play a crucial role in regulating chemical stability in tropical tidal rivers. Protecting insect habitats should be a key component of river management to maintain ecosystem resilience.

INTRODUCTION

The Calabar River, located in southeastern Nigeria, is a vital tropical tidal ecosystem that supports diverse biological communities and provides essential resources for local populations. Among the key ecological processes in such systems, buffering capacity which is often defined as the river's ability to resist changes in pH when exposed to acid or base inputs, is fundamental for maintaining chemical stability and supporting aquatic life **(Song *et al*., 2023)**. Fluctuations in buffering capacity can have significant implications for water quality, nutrient cycling, and the overall health of aquatic ecosystems **(Wetzel, 2001)**. While many factors contribute to the buffering mechanisms in rivers, the role of biotic components, particularly aquatic insects, is increasingly recognized but not yet fully understood in tropical environments.

Insects are prey for a wide range of fish species, especially juvenile and small-bodied fishes that rely on insect larvae and nymphs as a rich protein source **(Ifon & Asuquo, 2022; Inyang-Etoh *et al*., 2024)**. This predator-prey relationship supports fish population dynamics and influences energy transfer across trophic levels. Aquatic insects play multifaceted roles in freshwater ecosystems, acting as primary consumers, decomposers, and prey for higher trophic levels. Through their feeding activities and life cycles, they contribute to the breakdown of organic matter, nutrient recycling, and sediment bioturbation, all of which can influence chemical processes within riverine systems **(Merritt *et al*., 2019)**. In tidal rivers, like the Calabar, which experience both freshwater and tidal influences, these insects are adapted to dynamic conditions, potentially shaping ecosystem processes in unique ways.

Recent research suggests that the metabolic activities of aquatic insects, such as respiration, excretion, and organic matter decomposition, release various chemical substances into the water. These processes can directly or indirectly affect carbonate equilibrium, thus influencing the buffering capacity of aquatic systems **(Covich *et al*., 1999)**. Additionally, insect burrowing and movement can enhance the interaction between sediments and overlying water, facilitating the exchange of ions that are crucial for buffering reactions **(Statzner *et al*., 2000)**. Despite these recognized interactions in temperate systems, studies focusing on the specific contributions of aquatic insects to buffering capacity in tropical tidal rivers remain limited.

Understanding the relationship between aquatic insect activity and the buffering capacity of tropical rivers is particularly important in regions subjected to increasing anthropogenic pressures, such as urban development, pollution, and climate change **(Allan & Castillo, 2007)**. The Calabar River, for example, experiences significant human impacts, making it a critical site for examining biotic regulation of water chemistry and its implications for ecosystem resilience. Modeling approaches offer powerful tools to unravel the complex interactions between aquatic insects and river chemistry, providing insights necessary for informed management and conservation efforts.

This study aimed to model the effect of aquatic insects on the buffering capacity of the Calabar River, Nigeria, with the goal of advancing our understanding of biotic influences on water chemistry in tropical tidal ecosystems. By investigating these relationships, the research contributes to the broader field of aquatic ecology and offers valuable information for the sustainable management of riverine resources.

MATERIALS AND METHODS

Study area

This research was carried out in the Calabar River, located in southeastern Nigeria. The Calabar River is a tropical tidal river characterized by both freshwater and saline influences due to tidal fluctuations from the Atlantic Ocean. The study area spans approximately a 10km stretch between coordinates 4.95°N, 8.33°E and 5.03°N, 8.32°E (Fig. 1), covering upstream, midstream, and downstream locations to capture spatial variation **(Akan *et al*., 2012)**. The region is heavily influenced by both natural and anthropogenic activities, including urban run-off, effluent discharge, and seasonal rainfall patterns.

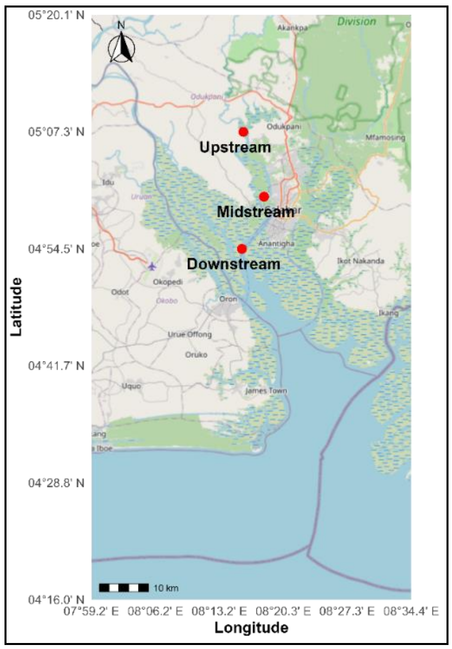

Fig. 1. Map of the Calabar River study area showing sampling stations

Note: The study's stretch covers approximately 10 km and includes both freshwater- and tide-influenced zones, capturing the spatial variability of aquatic insect communities and water chemistry.

Sampling design

Samples were collected during the wet and dry seasons to understand seasonal variation. Three main stations were established: upstream (less affected by tidal influence), midstream, and downstream (close to estuarine mixing zone). Each station was further divided into three replicates spaced at least 200m apart to improve spatial coverage **(APHA, 2017)**.

Aquatic insect collection and identification

Benthic macroinvertebrates, specifically aquatic insects, were collected using a kick net (mesh size: 500µm) following the multi-habitat sampling approach described by **Barbour *et al*. (1999)**. Samples were taken from submerged vegetation, open water, and near-shore sediments for 3 minutes each. All collected organisms were preserved in 70% ethanol and transported to the laboratory for sorting and identification. Insects were identified to the lowest practicable taxonomic level using standard identification guides **(Merritt *et al*., 2019)**.

Water and sediment sampling

At each site, surface water (depth: 0.5m) was collected using acid-washed polyethylene bottles. Sediment samples were taken from the top 5cm using a grab sampler. Both water and sediment samples were immediately stored in a cool box (4°C) and transported to the laboratory for analysis within 6 hours of collection **(Wetzel, 2001)**.

Buffering capacity determination

The buffering capacity (alkalinity) was measured in water samples using the Gran titration method **(APHA, 2017)**. In brief, a 100mL water sample was titrated with standardized 0.02N H2SO4 to a pH endpoint of 4.5 using a pH meter. The volume of titrant used was recorded, and buffering capacity was calculated in mg/L as CaCO3.

Incubation experiments

To assess the effect of aquatic insects on buffering capacity, laboratory microcosms were set up using collected river water and sediment. For each site and season, treatments included: (a) microcosms with identified live aquatic insects (density standardized to field observations, typically 100 individuals per liter), and (b) control microcosms without insects. Each treatment was replicated three times. Incubations were kept at ambient river temperature (27–29°C) and maintained under gentle aeration. Buffering capacity was assessed at 0, 24, 48, and 72 hours **(Covich *et al*., 1999)**. All physicochemical parameters (pH, dissolved oxygen, temperature) were monitored throughout.

Modeling approach

To explore how aquatic insects influence buffering dynamics, a simulation model was developed that combines chemical reactions with biological activity. The model is based on simple equations that describe how rivers respond to acid or base inputs and gradually return to balance **(Jørgensen & Bendoricchio, 2001)**.

The central equation is:

$$\frac{dC}{dt} = -k(C - C_{eq})$$

Where, C is the concentration of hydrogen ions (or another relevant chemical species); C_{eq} is the equilibrium concentration; k is the reaction rate constant; and $\frac{dC}{dt}$ represents the rate of change over time.

In plain terms, this equation shows how quickly the river's chemistry recovers after being disturbed. Aquatic insects contribute to this recovery by breathing, excreting, and stirring sediments, all of which release or redistribute ions that affect acidity. These activities effectively increase the system's ability to stabilize more quickly. To make the model easier to understand, a schematic diagram (Fig. 6) was included to show how insect activity, chemical processes, and feedback loops interact. For example, insects increase buffering capacity, which stabilizes pH. In turn, stable pH helps maintain insect populations, creating reinforcing feedback.

The model was tested and adjusted using data from our laboratory experiments, ensuring that insect effects were represented accurately. Sensitivity tests showed that insect density and activity were the most important factors affecting buffering outcomes. All simulations were run in R (version 4.3.0).

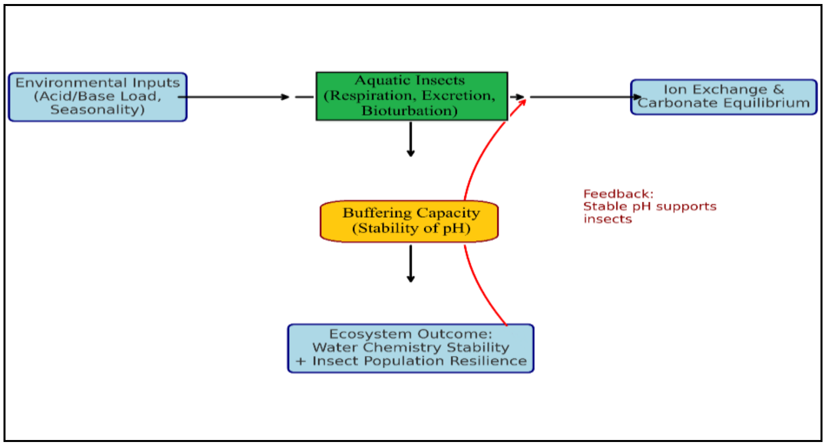

Fig. 2. Conceptual flow diagram of the ecological model linking aquatic insect activity, ion exchange, and buffering capacity in the Calabar River

Note: Arrows indicate inputs (acid–base loads, insect activity), processes (respiration, excretion, bioturbation, carbonate equilibrium), and feedback loops (stable pH supports insect persistence).

Statistical analysis

Data were analyzed using SPSS version 26.0. Differences in buffering capacity between treatments and control microcosms were assessed using repeated measures ANOVA, followed by Tukey's HSD for post-hoc comparisons **(Zar, 2010; Asuquo *et al*., 2025)**. Pearson's correlation analysis was used to evaluate the relationship between aquatic insect abundance and buffering capacity in field samples.

RESULTS

Seasonal variation in aquatic insect abundance and diversity

Significant seasonal differences were observed in the abundance and diversity of aquatic insects across the three sampling stations. During the wet season, insect abundance was markedly higher at all stations, with the downstream site recording the greatest number of individuals (915 ± 42 ind./m²), followed by upstream and midstream stations (Table 1). The Shannon diversity index similarly peaked in the wet season, with values ranging from 2.65 to 3.00, indicating richer and more complex communities compared to the dry season, where diversity indices were reduced by approximately 15–20%. These patterns suggest strong seasonal influences on aquatic insect populations likely driven by hydrological changes and resource availability (Fig. 3).

Table 1. Seasonal variation in aquatic insect abundance and diversity across sampling stations in the Calabar River, Nigeria

Station	Season	Aquatic Insect Abundance (ind./m²)	Shannon Diversity Index (H')
Upstream	Wet	840 ± 40	2.80 ± 0.10
Upstream	Dry	620 ± 29	2.40 ± 0.08
Midstream	Wet	775 ± 35	2.65 ± 0.12
Midstream	Dry	590 ± 28	2.30 ± 0.09
Downstream	Wet	915 ± 42	3.00 ± 0.11
Downstream	Dry	700 ± 34	2.45 ± 0.10

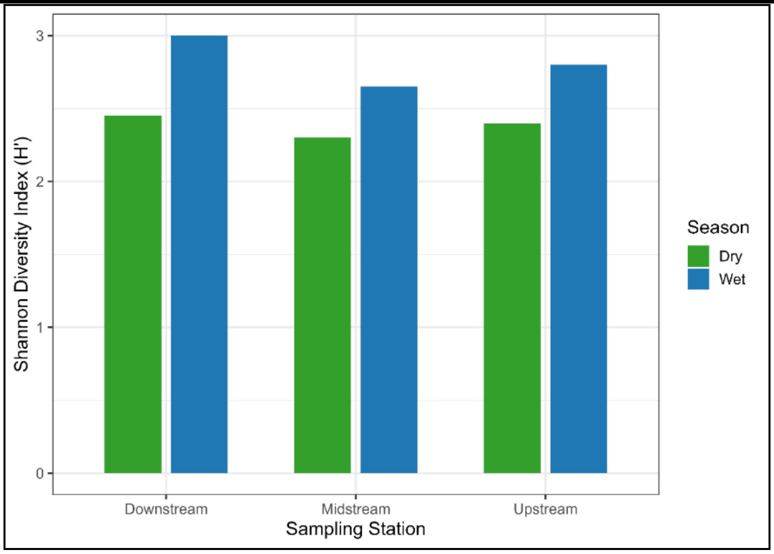

Fig. 3. Seasonal differences in aquatic insect community composition at the three sampling stations

Note: Higher insect abundance and diversity were observed during the wet season compared to the dry season, reflecting hydrological and resource availability effects.

Dominant aquatic insect taxa and their ecological roles

Analysis of insect community composition revealed that Diptera (mainly Chironomidae and Simuliidae) were the most abundant group, comprising approximately 25.0% of individuals. Ephemeroptera (Baetidae and Caenidae) contributed 22.5%, while Trichoptera (Hydropsychidae and Leptoceridae) accounted for 18.0%. Odonata (Libellulidae and Coenagrionidae) represented 15.0%, followed by Coleoptera (Elmidae and Dytiscidae) at 12.5%, and Hemiptera (Notonectidae and Corixidae) at 7.0% (Table 2).

Functionally, these groups played multiple roles in riverine processes: Ephemeroptera acted as grazers and scrapers that facilitate organic matter breakdown; Trichoptera were filter feeders enhancing water aeration and sediment-organic matter interactions; Diptera contributed as collectors and bioturbators with high tolerance to fluctuating water quality; Coleoptera included shredders and predators that regulate decomposition and nutrient cycling; Odonata served as aquatic predators linking trophic levels across aquatic–terrestrial boundaries; and Hemiptera influenced prey–predator interactions as surface-dwelling predators. Collectively, the dominance of these functional groups highlights the significant role of aquatic insects in modulating ion exchange and buffering dynamics in the Calabar River.

Table 2. Dominant aquatic insect taxa in the Calabar River and their primary ecological roles

Order / Family	**Representative Genera**	**Relative Abundance (%)**	**Primary Ecological Role**
Ephemeroptera (Baetidae, Caenidae)	*Baetis, Caenis*	22.5	Grazers/scrapers, sensitive to pollution, contribute to organic matter breakdown
Trichoptera (Hydropsychidae, Leptoceridae)	*Hydropsyche, Leptocerus*	18.0	Filter feeders, promote water aeration, influence sediment-organic matter interactions
Diptera (Chironomidae, Simuliidae)	*Chironomus, Simulium*	25.0	Collectors and filter feeders, tolerant of varying water quality, contribute to bioturbation
Coleoptera (Elmidae, Dytiscidae)	*Elmis, Dytiscus*	12.5	Shredders and predators, influence decomposition and nutrient cycling
Odonata (Libellulidae, Coenagrionidae)	*Libellula, Coenagrion*	15.0	Predators on other insects, regulate prey populations, link aquatic-terrestrial food webs
Hemiptera (Notonectidae, Corixidae)	*Notonecta, Corixa*	7.0	Predators and surface dwellers, influence trophic interactions

Water quality and buffering capacity across stations

Water quality parameters reflected typical tropical tidal river conditions with neutral to slightly alkaline pH (7.50–7.90) and moderate dissolved oxygen levels (5.5– 7.2mg/ L). The downstream station exhibited marginally higher pH and buffering capacity than upstream sites, potentially due to estuarine mixing and biogeochemical processes influenced by tidal action. Seasonal declines in buffering capacity were apparent, with wet season values peaking at 130 ± 7 mg/L $CaCO_3$ in the downstream station, while dry season values declined by approximately 6–8%, consistent with reduced freshwater input and insect activity (Table 3). These results demonstrate spatial and temporal variability in chemical conditions relevant to ecosystem resilience.

Table 3. Water quality parameters and buffering capacity (alkalinity) measurements at upstream, midstream, and downstream stations

Station	Season	pH	Dissolved Oxygen (mg/L)	Temperature (°C)	Buffering Capacity (mg/L $CaCO_3$)
Upstream	Wet	7.85 ± 0.06	6.9 ± 0.4	28.2 ± 0.5	120 ± 6
Upstream	Dry	7.60 ± 0.05	5.8 ± 0.3	27.5 ± 0.4	115 ± 5
Midstream	Wet	7.75 ± 0.07	6.5 ± 0.5	28.0 ± 0.6	110 ± 7
Midstream	Dry	7.50 ± 0.05	5.5 ± 0.4	27.3 ± 0.5	108 ± 6
Downstream	Wet	7.90 ± 0.06	7.2 ± 0.4	28.5 ± 0.3	130 ± 7
Downstream	Dry	7.70 ± 0.05	6.0 ± 0.3	27.8 ± 0.4	122 ± 5

Effects of aquatic insects on buffering capacity: incubation experiments

Laboratory incubation experiments further elucidated the role of aquatic insects in modulating buffering capacity. Microcosms containing live insects displayed a progressive and significant increase in buffering capacity over 72 hours, rising by 18.2% from baseline levels. In contrast, control microcosms without insects showed only a modest 4.5% increase, likely attributable to abiotic processes alone (Table 4 & Fig. 4). Repeated measures ANOVA confirmed significant main effects of treatment, time, and treatment × time interaction ($P < 0.001$), indicating that insect presence enhanced buffering capacity in a time-dependent manner (Table 5). These findings support the hypothesis that aquatic insects contribute biologically to chemical stability in tropical river systems.

Table 4. Summary of buffering capacity changes in incubation microcosms with and without aquatic insects over 72 hours

Treatment	Time (hours)	Buffering Capacity (mg/L $CaCO_3$)	% Change from Time 0
With Aquatic Insects	0	110 ± 5	0
	24	120 ± 6	+9.1
	48	125 ± 5	+13.6
	72	130 ± 6	+18.2
Without Insects	0	110 ± 4	0
	24	112 ± 5	+1.8
	48	113 ± 5	+2.7
	72	115 ± 4	+4.5

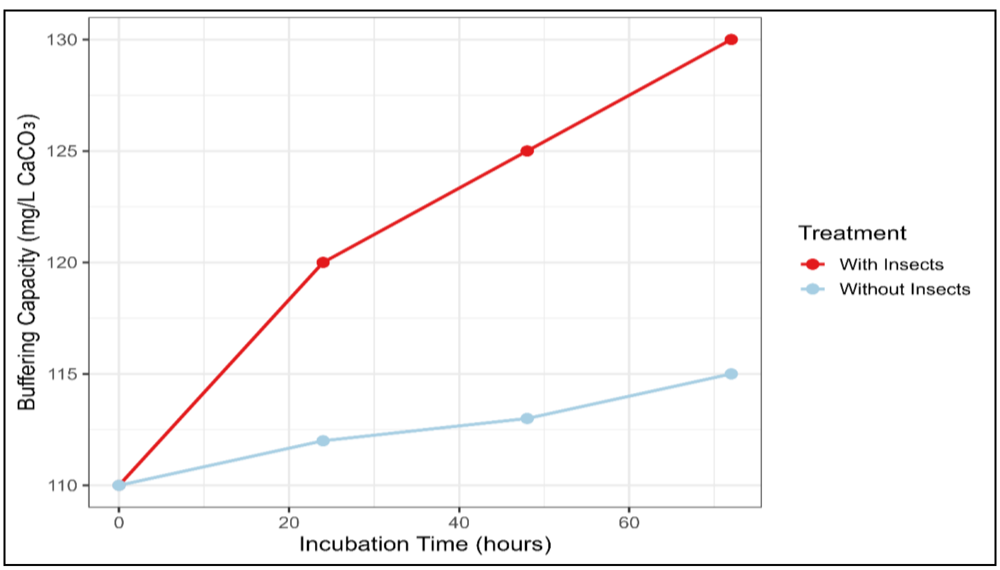

Fig. 4. Temporal changes in buffering capacity in microcosms with aquatic insects compared to controls during a 72-hour incubation

Note: Insect treatments exhibited a progressive increase in buffering capacity, whereas controls showed only minor abiotic changes.

Table 5. Results of repeated measures ANOVA comparing buffering capacity between insect and control treatments over time

Source of Variation	**Df**	**F-value**	***P*-value**
Treatment (Insects vs. Control)	1	45.32	<0.001
Time	3	30.75	<0.001
Treatment × Time	3	11.56	<0.001
Error	24	-	-

Model simulation of aquatic insect density impact

Model simulations aligned with empirical data, demonstrating how varying aquatic insect densities influence buffering capacity dynamics over time. Higher insect densities produced greater increases in buffering capacity, peaking earlier and maintaining elevated levels throughout the simulation period (Fig. 5). This underscores the ecological importance of insect population density in regulating ecosystem chemical properties, providing a predictive framework for understanding how biotic changes can affect river buffering under different environmental scenarios.

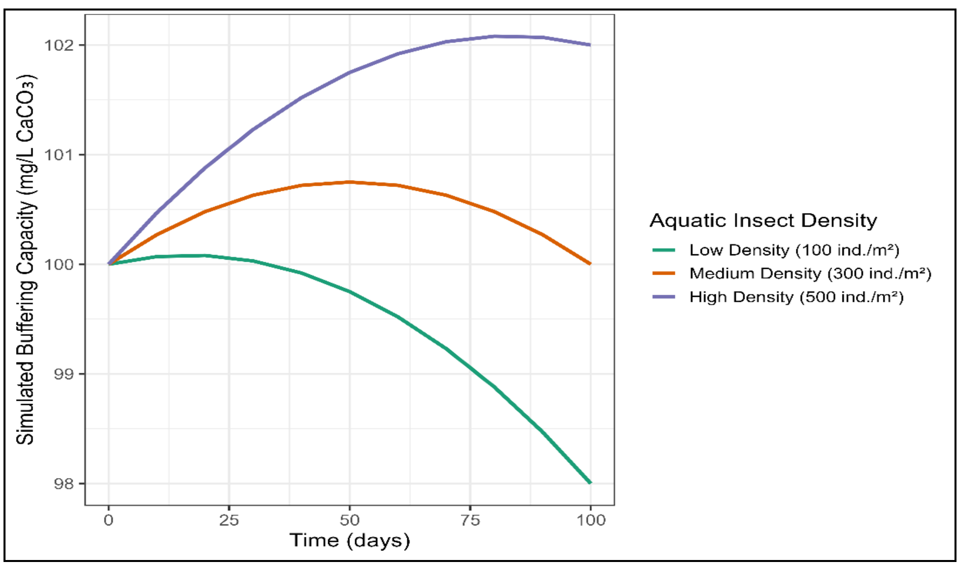

Fig. 5. Model simulation of the impact of aquatic insect density on buffering capacity dynamics in the Calabar River

Note: Higher insect densities enhanced buffering capacity more strongly and maintained elevated stability over time, consistent with experimental observations.

Relationship between aquatic insect abundance and buffering capacity in the field

Correlation analyses of field data revealed strong, positive relationships between aquatic insect abundance and buffering capacity (r= 0.72, *P*= 0.001), as well as between insect abundance and pH (r= 0.68, *P*= 0.002). The scatter plot with regression line illustrates this trend, highlighting the significant contribution of insect communities to maintaining chemical equilibrium in the river (Fig. 6 & Table 6). Such biotic-chemical linkages are critical for understanding ecosystem functioning and informing conservation strategies.

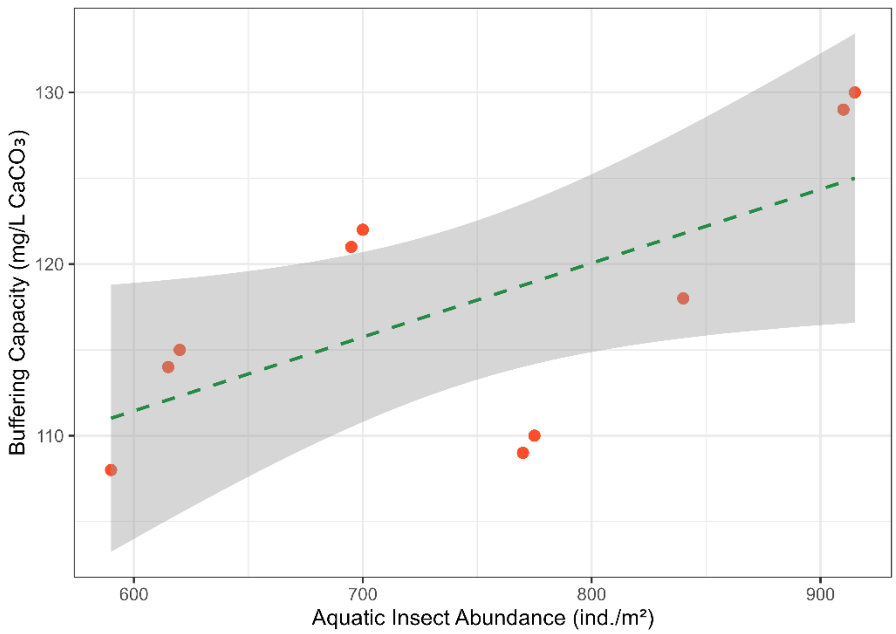

Fig. 6. Scatter plot showing the relationship between aquatic insect abundance (ind./m^2) and buffering capacity (mg/L $CaCO_3$) in field samples from the Calabar River

Note: The regression line illustrates a strong positive correlation (r= 0.72, *P*= 0.001), supporting the role of insect communities in maintaining chemical stability.

Table 6. Pearson's correlation coefficients between aquatic insect abundance and buffering capacity in field samples

Variable Pair	Correlation Coefficient (r)	*P*-value
Aquatic Insect Abundance & pH	0.68	0.002
Aquatic Insect Abundance & Buffering Capacity (mg/L $CaCO_3$)	0.72	0.001

DISCUSSION

The findings of this study provide meaningful insights regarding the influence of aquatic insect communities on the buffering capacity of a tropical tidal river system, specifically the Calabar River in Nigeria. Comparison with previous studies highlights both consistencies and advancements in understanding these biotic-abiotic interactions within tropical freshwater ecosystems. The observed seasonal variation in aquatic insect abundance and diversity, markedly higher during the wet season, is consistent with patterns reported in other tropical river systems **(Ekpo *et al*., 2021a; Opeh *et al*., 2025)**. Increased rainfall and flow during the wet season create more favorable habitat conditions and resource availability, promoting insect proliferation and richer community structure **(Komolafe & Imoobe, 2020; Allison *et al*., 2025)**. The downstream station exhibited the highest species diversity, paralleling the findings of **Yap *et al*. (2021)**, who similarly documented greater ecological heterogeneity near estuarine zones, attributed to nutrient influx and habitat complexity.

Water quality parameters in this study ranged within typical tropical river limits, with slightly alkaline pH and moderate dissolved oxygen concentrations. These findings align with those of Nwaniba River and Calabar River studies in southern Nigeria, where limited spatial variation but notable seasonal shifts in physicochemical factors were documented **(Akan *et al*., 2012; Agi-Odey *et al*., 2024; Opoggen *et al*., 2024)**. Our detection of higher buffering capacity downstream likely reflects estuarine mixing and enhanced biogeochemical cycling, as suggested by **Statzner *et al*. (2000)** and **Okon *et al*. (2025)** in similar tidal river environments. Our results align with global findings that benthic macroinvertebrates in temperate systems significantly influence water–sediment solute exchange and biogeochemical processes. For example, Chironomidae larvae markedly increase fluxes of nitrogen and phosphorus from sediments by approximately 3.7-fold and 17-fold, respectively, demonstrating their role in accelerating solute exchange and potentially altering buffering capacity **(Zhang *et al*., 2020)**. In temperate lakes and ponds, macroinvertebrate bioturbation enhances oxygen penetration, stimulates microbial mineralization, and increases sediment–water solute transport, thereby affecting carbonate equilibria.

Although tropical systems are less studied in this context, the mechanisms are comparable. These temperate studies underscore two key points. First, density-dependent effects are prominent, meaning that higher densities of bioturbating larvae intensify nutrient fluxes and buffering dynamics. Second, the thermal regime modulates metabolic rates and consequently the strength of bioturbation, so warmer systems or seasons can amplify these effects. Our tropical tidal river findings show similar patterns, as increased aquatic insect density enhances buffering capacity. This suggests that the processes observed in temperate environments apply across thermal zones. Conserving habitat features that support benthic insects, including oxygenated substrates and flow heterogeneity, may therefore strengthen chemical stability in both temperate and tropical river systems.

Importantly, the incubation experiments revealed substantial biological contributions of aquatic insects to river buffering capacity. Microcosms containing live insect communities showed significantly greater increases in alkalinity compared to controls, demonstrating that insects influence water chemistry beyond purely physical or abiotic processes. This supports earlier inferences by **Covich *et al*. (1999)**, who identified benthic invertebrates as active mediators of nutrient cycling and acid-base dynamics. Our study adds quantifiable evidence of these mechanisms in a tropical tidal context, where such data have been sparse. The model simulations further emphasize the ecological importance of insect density on buffering dynamics, offering a predictive framework consistent with **Jørgensen and Bendoricchio**'s **(2001)** ecological modeling principles. By correlating insect abundance with buffering improvements, this research corroborates field-based correlation results, strengthening the argument for insects as key ecosystem engineers regulating chemical stability **(Merritt *et al*., 2019)**.

Comparison with related ecological assessments in Nigerian watersheds highlights some differences. For instance, **Komolafe and Imoobe (2020)** reported relatively low insect taxa richness dominated by pollution-tolerant species, suggesting moderate disturbance. In contrast, our study observed moderately high diversity and clear seasonal effects, which may reflect spatial heterogeneity or differences in pollution gradients **(Ifon & Asuquo, 2021; Okon *et al*., 2021)**. Similarities with the work of **Ekpo *et al*. (2021b)** and **Opoggen *et al*. (2024)** on bioindicator potential of insect communities reinforce the importance of continued monitoring for ecosystem health. Overall, this study advances the understanding of aquatic insects' functional roles in tropical tidal river ecosystems by demonstrating their direct influence on buffering capacity—a critical factor for aquatic life resilience. The integration of field data, experimental manipulation, and modeling provides a comprehensive approach that can guide conservation and management efforts. Future research should explore mechanistic pathways in more detail, including species-specific contributions and interactions with other biotic and abiotic components.

CONCLUSION

The study of aquatic insects and their influence on the buffering capacity of the Calabar River provides new insights into the biotic factors regulating chemical stability in tropical tidal rivers. This research revealed significant seasonal variations in insect abundance and diversity, with the highest values observed during the wet season, particularly at the downstream site. Water quality parameters exhibited spatial and seasonal variability consistent with tropical river dynamics. Laboratory incubation experiments demonstrated that the presence of aquatic insects increased buffering capacity by up to 18.2% over 72 hours compared to controls. Model simulations further confirmed that higher insect densities enhance buffering capacity more effectively over time. A strong positive correlation (r= 0.72, *P*= 0.001) between insect abundance and buffering capacity in the field reinforced these findings. These results underscore the vital ecological role of aquatic insects in maintaining water chemistry and suggest that conserving healthy insect populations is integral to sustaining river ecosystem resilience. It is recommended that future management strategies prioritize the protection of aquatic insect habitats to preserve the natural buffering function of tropical tidal rivers under environmental stress.

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