International Journal of Aquatic Research and Environmental Studies 6(1) 267-283 2026

Analysis of microbial and chemical exchange processes at the groundwater–surface water interaction zone

Prashanth Kumar Koochana[1*]; Ganga Bhavani T[2];
Valli Nachiyar C[3]; Saravanan A[4]; Ashish Verma[5];
Ashutosh Kulkarni[6]; Deepika Sharma[7]; Baskaran Kuppusamy[8]

Received: 07 January 2026; Revised: 23 January 2026; Accepted: 13 March 2026; Published: 20 April 2026

Abstract

This essay examines the hydrological, chemical, and microbial interactions coupled with each other that occur at the interface of groundwater and surface water (hyporheic zone). The aim is to learn the role of hydrological connectivity and redox gradients in controlling the dynamics of microbial communities and nutrient conversion, which in turn affects the quality of water and ecosystem processes. A transect sampling method was used to sample the interaction zone to obtain surface water and groundwater samples. On-site measurements were done to measure physicochemical parameters (temperature, pH, dissolved Oxygen, electrical conductivity, and redox potential). The structure of microbial communities was studied by ATP analysis and 16S rRNA gene sequencing. The standard laboratory methods were used to determine the chemical components (nutrients and dissolved organic carbon). The processes of hydrology and geochemistry were assessed based on the law of Darcy, the advection-dispersion equation, and numerical modeling, with the help of statistical techniques such as correlation and principal component analysis. The findings indicated that there were high hydraulic connectivity values with gradients between 0.002 and 0.015, which are indicative of active exchange processes. Surface water was oxic (DO: 6.8 mg/L; redox: +120 mV) and groundwater was suboxic

---

[1*]-Assistant Professor, Department of Chemistry Vardhaman College of Engineering, Shamshabad, Hyderabad, India. Email: prashanth1698@vardhaman.org, ORCID: https://orcid.org/0000-0002-2581-994X

[2]- Assistant Professor, Department of Computer Science Engineering (Cyber Security), Pragati Engineering College, Kakinada, Andhra Pradesh, India. Email: gangabavanimanda@gmail.com,
ORCID: https://orcid.org/0009-0005-3160-2762

[3]- Professor, Department of Research, Meenakshi Academy of Higher Education and Research, Chennai, Tamil Nadu, India. Email: vnachiyar@maher.ac.in, ORCID: https://orcid.org/0000-0003-1574-1672

[4]- Professor, Department of Mechanical Engineering, Aditya University, Surampalem, Andhra Pradesh, India. Email: saravanan.a@adityauniversity.in, ORCID: https://orcid.org/0009-0001-3085-722X

[5]- Centre of Research Impact and Outcome, Chitkara University, Rajpura, Punjab, India.
Email: ashish.verma.orp@chitkara.edu.in, ORCID: https://orcid.org/0009-0008-5763-2144

[6]- Associate Professor, DESH, Vishwakarma Institute of Technology, Pune, Maharashtra, India.
Email: ashutosh.kulkarni@vit.edu, ORCID: https://orcid.org/0000-0002-7265-3540

[7]- School of Sciences, Noida International University, Uttar Pradesh, India.
E-mail: deepika.sharma@niu.edu.in, ORCID: https://orcid.org/0009-0002-4171-8564

[8]- Scientist, Central Research Laboratory, Meenakshi Medical College Hospital & Research Institute, Meenakshi Academy of Higher Education and Research, Chennai, Tamil Nadu, India.
Email: baskark@maher.ac.in, ORCID: https://orcid.org/0009-0008-0831-7391

*Corresponding author

DOI: 10.70102/IJARES/V6I1/6-1-18

to anoxic (DO: 3.2 mg/L; redox: -50 mV). The electrical conductivity of groundwater (780 µS/cm) was greater than that of surface water (420 µS/cm). The Firmicutes and Actinobacteria were the most dominant microbial communities (28-46%), and the diversities of the hyporheic zone were the highest. The occurrence of the processes of nitrification and denitrification was evidenced by the occurrence of the nutrient gradient, indicating high concentrations of nitrate in the surface waters (8.5mg/L) and ammonium in groundwater (4.6mg/L). The paper shows that the groundwater surface water interface represents a dynamic biogeochemical reactor wherein hydrological flow, redox, and microorganisms work together to balance nutrient cycling and contaminant conversion. These observations show the importance of such an interface in maintaining water quality and the need to have integrated monitoring and modeling systems.

Keywords: Groundwater–surface water interaction, Hyporheic zone, Microbial dynamics, Nutrient cycling, Redox processes

Introduction

The boundary layer between surface and groundwater, also referred to as the hyporheic zone, is quite critical in regulating biogeochemical processes in aquatic organisms. This dynamic interface helps to exchange nutrients, dissolved organic matter, gases, and microbial communities, thus affecting the water quality, ecosystem productivity, and contaminant transport (Modie *et al.*, 2022). Microbial processes which are predominant in this area include nitrification, denitrification, sulfate reduction, and organic matter degradation since redox gradients and diverse energy sources are present. Meanwhile, interactions and exchanges of nutrients and trace metals significantly affect the subsurface and surface water systems as well (Krause *et al.*, 2024). Such coupled microbial and chemical processes are important to understand how to sustainably use water resources, especially in the context of increased anthropogenic stressors such as agriculture, urbanization, and climate change (Das, 2025). The boundary layer between surface and groundwater, also referred to as the hyporheic zone, is quite critical in regulating biogeochemical processes in aquatic organisms. This dynamic interface helps to exchange nutrients, dissolved organic matter, gases, and microbial communities, thus affecting the water quality, ecosystem productivity, and contaminant transport (Modie *et al.*, 2022). Microbial processes which are predominant in this area include nitrification, denitrification, sulfate reduction, and organic matter degradation since redox gradients and diverse energy sources are present. In the meantime, the interchange and interactions of nutrients and trace metals also impact the subsurface and surface water systems (Krause *et al.*, 2024) considerably. Such coupled microbial and chemical processes are important to understand how to sustainably use water resources, especially in the context of increased anthropogenic stressors such as agriculture, urbanization, and climate change (Das, 2025).

The main aim of this research is to critically examine the microbial and chemical exchange processes that take place at the groundwater-surface water interaction zone. The research seeks to understand the spatial and temporal variations of the microbial community structure and their contributions towards biogeochemical variations in terms of their functions. It also aims to examine the transport, transformation, and interchange of the significant chemical components, such as nutrients, dissolved organic substances, and pollutants, within this interface. Moreover, the paper aims to investigate the interdependence of microbial activity and chemical gradients, and determine how these two interact to assess the impact of environmental conditions and anthropogenic influences on these two processes in order to enhance the dynamics of water quality and ecosystem processes.

The hypothesis of this study is that a zone of groundwater-surface water interaction can be a biogeochemical hotspot that is actively subjected to microbial activity that results in the crucial regulation of chemical transformations. It is also proposed that the changes in hydrological conditions and nutrient inputs change the composition of microbial communities, which further affects the rate and direction of chemical exchange processes.

Although there is an increased interest in groundwater-surface water interactions, very little is known about the combined role of microbial interactions and chemical transactions in this interface (Gaur *et al.*, 2022). Most of the current studies tend to consider either hydrochemical analysis or microbial ecology individually, and fewer studies focus on studying their interactions. Furthermore, high-resolution spatial and temporal analyses of these processes are deficient, especially when subjected to different environmental regimes and human stressors. This lack of knowledge restricts the ability to predict the ecosystems and control the water resources.

The work adds value to the field since it provides a comprehensive examination of the interactive processes of microbes and chemicals at the interface of groundwater/surface water. It involves microbiology, chemistry, and hydrology methods to give a holistic picture of the system. The paper also presents better analytic models of evaluating the interactions of biogeochemical processes and the importance of environmental drivers in determining the processes. It is anticipated that the results will aid in improved water quality management measures, improved predictive modeling of contaminant transportation, and guide sustainable conservation of ecosystems.

Section 1 of the article begins with an Introduction where the hyporheic zone is defined as an active zone between the groundwater and surface water that regulates microbial and chemical transfers to influence nutrient cycling, water quality, and ecosystem processes in both natural and anthropogenic stress. Followed by Section 2, the Literature Review focuses on the earlier research involving a combination of hydrochemical and microbial analyses, redox processes, nutrient conversions, and contaminant mitigation. In section 3, Materials and Methods, the study area, sampling (in transects), microbial and chemical analysis, hydrological and geochemical modeling, statistical methods, and quality assurance procedures are explained. Results include hydrological gradient, physicochemical properties, microbial structure, nutrient dynamics, and modeling in Section 4. The Discussion in section 5 provides meaning to coupled hydrological-biogeochemical processes and ecological implications, and the Conclusion in section 6 demonstrates the hyporheic zone as a biogeochemical hotspot and outlines future research directions.

Literature Review

Surface water-groundwater interaction is a significant factor in the regulation of hydrological connectivity, the flow of nutrients, and ecosystems in aquatic conditions. The hyporheic zone as a dynamic interface allows two-way exchange of water, solutes, and energy and affects physical and biogeochemical processes (Larned *et al.*, 2015; Fleckenstein *et al.*, 2010). The interdisciplinary methods of field measurements, modeling, and hydrochemical analyses have been highlighted to understand these interactions better (Lewandowski, Meinikmann and Krause, 2020).

The recent research is increasingly emphasizing the need to couple the hydrochemical and microbial perspectives. A combination of microbial analysis and hydrochemical indicators will give a better understanding of the processes of nutrient cycling and transformation in the hyporheic zone (Zhu *et al.*, 2020). On the same note, the extraction of seasonal groundwater causes a major change in the microbial community in the surface-groundwater mixing areas (Lee, Lee and Unno, 2018). These results are consistent with the results in urban streams, where microbial activity leads to a strong effect on the flux of organic matter and nutrient transformation (Mladenov *et al.*, 2022).

The microbial dynamics are tightly related to the conditions of redox and the availability of nutrients. Nitrification and denitrification revealed ammonium and nitrate transitions that depend on oxygen dynamics and gradients, which change with flow patterns (Yan *et al.*, 2022; Li *et al.*, 2022). The hyporheic zone is a reactive interface, and changing redox conditions promote more diversity and metabolic activity among microbes, which leads to faster nutrient cycling (Lee, Lee and Unno, 2018; Ottosen *et al.,* 2020).

The focus of hydrochemical research has been on the role of hydrological forcing and the nature of the aquifer on solute movement. Modifications in water transfers can change the patterns of interaction and hydrochemical profiles of groundwater (Yuan *et al.*, 2020), but streambed properties and the heterogeneity of the aquifer can greatly regulate surface-subsurface water fluxes (Tripathi *et al.*, 2021; Wang *et al.*, 2023). Reactive transport models also confirm that the transformations of nitrogen and carbon across the interface are mediated by microorganisms (Li *et al.*, 2021).

The research on the transport and fate of the contaminants in these areas has also gained momentum in the emerging research. In the interaction zone, microbial and hydrogeochemical transformations of antibiotics, PFAS, and other trace pollutants take place (Fu *et al.*, 2022; Tokranov *et al.*, 2021). Combined tests demonstrate that these locations are natural reactors that decrease pollutants and maintain the balance of nutrients (Ottosen *et al.*, 2020; Liang *et al.*, 2023).

Overall, literature indicates that groundwater–surface water interaction zones are biogeochemical hotspots controlled by hydrological, chemical, and microbial processes. Nevertheless, in spite of the advances, the integration of microbial dynamics with high-resolution hydrochemical and hydrological models is still scarce, and multidisciplinary solutions are needed to enhance predictive insights and the sustainable management of water resources.

Materials and Methods

Study Area Description

The experiment is done in representative groundwater-surface water contact area where there is active hydrological exchange between an aquifer and a nearby water body that is a surface water body. Porosity, permeability, and hydraulic gradients are assessed as hydrogeological properties of the site to gain insights into the dynamics of subsurface flow. Surface and subsurface water interaction is controlled by hydraulic gradients, and the exchange process is facilitated by the hydraulic gradients across the interface.

Sampling Design and Field Measurements

An organized system of sampling is adopted along transects in the surface water and groundwater interface. Field measurements are temperature, pH, dissolved Oxygen, electrical conductivity, and redox potential. The hydraulic gradient, on which groundwater flow direction depends, is calculated as:

$$i = \frac{\Delta h}{\Delta l} \tag{1}$$

I is the hydraulic gradient, Δh is the difference in hydraulic head, and Δl is the distance between the two points of measurement, as shown in equation (1). This parameter is very important in determining the direction of water exchange and the magnitude.

Microbial Analysis

High-throughput molecular and biochemical analysis was combined to study the abundance and structure of microbial communities. The total microbial biomass of samples of groundwater was first determined by an adenosine triphosphate (ATP) based assay. The concentrations of ATP were measured with a luminometer system, and ATP concentrations were then converted to an approximation of the bacterial cell counts, with empirically established relationships, to provide a rough estimate of microbial density in the samples.

In order to study the community further, the groundwater samples were filtered to settle the microbial cells on 0.45 µm membrane filters. The biomass collected was then subjected to genomic DNA extraction with a bead-beating protocol to aid cell lysis. Each sample was subjected to downstream molecular analysis by pooling the DNA extracted.

Bacterial communities were amplified using 16S rRNA V4 region primers (515F/806R primers), and sequenced using Illumina MiSeq (2x250 bp paired-end sequencing; ~50,000 reads/sample after filtering, n=24; QIIME2 pipeline with DADA2 denoising >99.9% of OTU clustering (97% similarity) of mothur was done because of its capacity to better handle uneven sequencing depth of the hyporheic zone (range: 42,000-68,000 reads). This method allowed revealing the trends of diversity in microorganisms and giving hints on the functional capabilities of microbial communities that inhabit the groundwater-surface water interface (Lee *et al.,* 2018). The kinetic equation of growth further modeled the dynamics of microbial growth, with substrate-limited growth conditions modeled using the Monod equation:

$$\mu\ \mu_{\max}\frac{S}{K_s+S} \qquad (2)$$

In equation (2) μ is the specific growth rate, $\mu_{\max}$ is the maximum growth rate, S is the substrate concentration, and K_s is the half-saturation constant. This association helps to relate the supply of nutrients and the dexterity of microbes in the zone of interaction.

Chemical Analysis

A combination of physicochemical conditions and dissolved elements defined the chemistry of groundwater as a combination of in situ measurements and laboratory techniques. To maintain in situ conditions, field parameters such as temperature, electrical conductivity, redox potential, and dissolved Oxygen were measured on the spot at the sampling sites using portable probes.

Sulfide and dissolved ferrous iron (Fe^{2+}) concentrations were measured on-site using portable kits that were based on standard HACH methods (method 8146 and 8131, respectively). These measurements gave instant information on the redox-sensitive species of the groundwater system.

Laboratory tests were performed to determine the amount of major cations, trace elements, and anions. Inductively coupled plasma atomic emission spectroscopy was used to measure dissolved metals like iron (Fe), manganese (Mn), and silicon (Si). The ion-exchange chromatography was used to analyze major anions, such as chloride (Cl^-), nitrite (NO_2^-), nitrate (NO_3^-), phosphate (PO_4^{3-}), and sulfate (SO_4^{2-}), and thus ion detection was very precise.

Non-purgeable organic carbon (NPOC) was obtained as total organic carbon (TOC) by using a TOC analyzer, which gives an estimate of the organic matter at the disposal of microbial metabolism. All these chemical parameters characterize the geochemical environment and nutritional value in the zone of interaction (Lee *et al.,* 2018). Besides measurements of concentration, the processes of chemical transport and transformation were measured based on the advection-dispersion equation:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - v\frac{\partial C}{\partial x} + R \qquad (3)$$

In equation (3), C is the concentration of the solute, t is the time, D is the dispersion coefficient, v is the flow velocity, and R represents terms of reaction, which include microbial-mediated transformations. This equation describes the movement and reactions of chemical constituents in the system.

Hydrological and Geochemical Modeling

PHREEQC v3.7.3 reactive transport was modeled with the aid of MODFLOW-6 and calibrated with field data (R^2=0.87

for DO profiles). PHREEQC was selected to be a strong speciation program at variable redox (e.g., Fe^{2+}/Fe^{3+}, NO_3^-/NH_4^+). The geochemical modeling software is used to model chemical interactions, reaction kinetics, and chemical speciation. These models are calibrated with field data to learn more about the dynamics of flows, solute transport, and reaction pathways that mediate microbial and chemical exchanges. The Darcy Law is used to simulate groundwater flow, which appears in porous media:

$$Q = -KA\frac{dh}{dl} \tag{4}$$

In equation (4), Q is discharge, K is hydraulic conductivity, A is cross-sectional area, and $\frac{dh}{dl}$ is hydraulic gradient. This model is linked to geochemical simulations to evaluate the processes of solute transport and reactions under varying environmental conditions.

Data Integration and Statistical Analysis

The acquired datasets were analyzed based on certain statistical procedures to determine correlations between the microbial communities and chemical parameters. The strength and direction of linear relationships among continuous variables of nutrient concentrations, dissolved oxygen, and microbial abundance were assessed using Pearson correlation analysis. Dependencies were further measured using simple linear regression models and multiple linear regression (MLR) models. Simple linear regression was used to identify the effect of each of the environmental variables on the microbial indicators, and the multiple linear regression was used to identify the effect of a combination of physicochemical parameters on the responses of the microbial communities. A Principal Component Analysis (PCA) was performed to decrease dimensions and identify some of the controlling factors. The method assisted in converting correlated variables into a collection of orthogonal terms that showed the important gradients that predetermined the variability of the system. All statistical analyses were performed in R (4.3.2) to ensure reproducible results and standardized processing of data.

Quality Assurance and Control

Calibrated measurements are taken with a caliper, and standardized measurements are carried out using standardized procedures in the laboratory. Replicates of samples, blanks, and reference standards are used to ensure precision and accuracy. The consistency and reliability of data are ensured by validation procedures.

Figure 1 shows a systematic workflow of the study, beginning with site characterization and sampling on the basis of transects to microbial, chemical, and hydrological analysis. It combines both model and statistical techniques in demonstrating the combined assessment of physical, chemical, and biological processes that are used to explain interactions of the groundwater-surface water system.

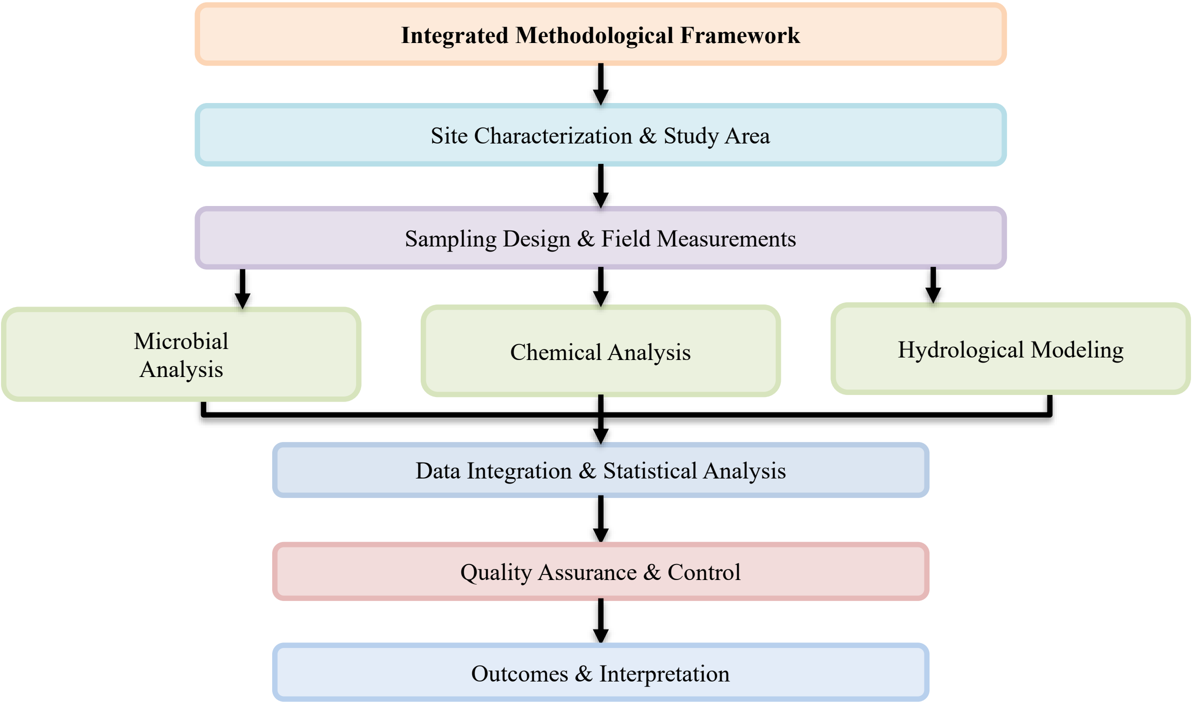

Figure 1: Integrated methodological framework for groundwater–surface water interaction analysis.

Results

Hydrological Characteristics of the Interaction Zone

There was a high hydraulic connectivity between the interface of the groundwater and surface water, which confirmed that there are active exchange processes. Hydraulic gradients across transects ranged from 0.002–0.015 (mean: 0.008 ± 0.004, n=24 piezometers; Equation 1), indicating spatially variable gaining (0.010–0.015, n=8) and losing (0.002–0.006, n=16) conditions (Figure 2). Groundwater discharge to the surface water (gaining) and recharge-dominated (losing) conditions were linked to areas with higher and lower gradients, respectively. These gradients were greatly influenced by seasonal variability, whereby during the monsoon season, the values were higher, thereby increasing advective transport, and during the dry season, the values were lower, therefore increasing the residence time in the subsurface. These modifications had a direct effect on solute movement and metabolic rate of microbes, and the role of hydraulic forcing in the regulation of exchange techniques is evident.

Figure 2 shows the spatial distribution of the hydraulic gradient in the sampling transects. It points out areas of gaining and losing conditions and demonstrates the varying hydrological connectivity between the groundwater-surface water interface. To represent changes in the intensity of flows, seasonal influence can be conceptually represented (e.g., monsoon vs. dry periods).

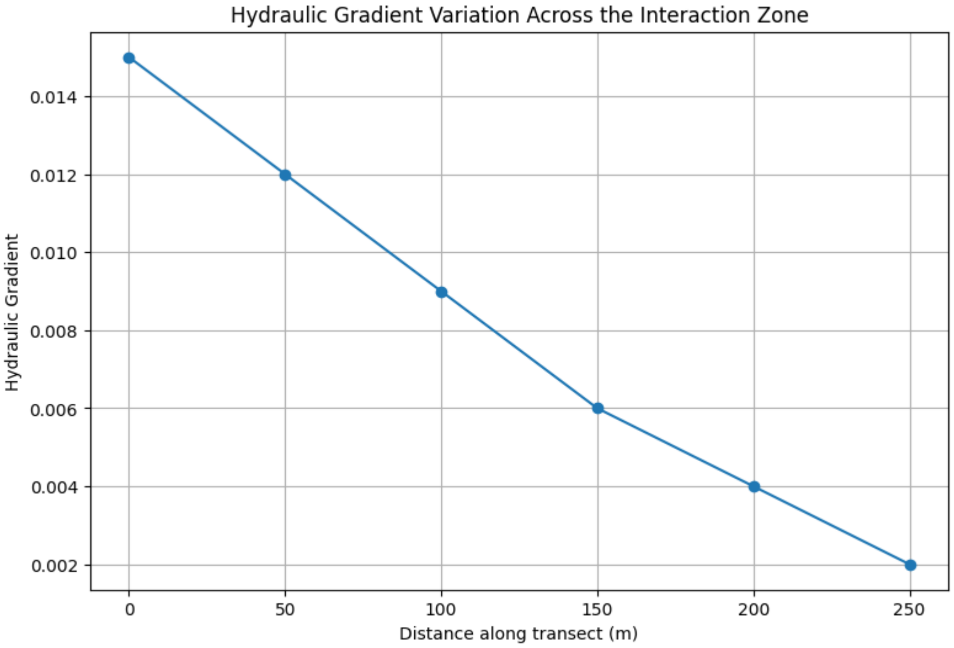

Figure 2: Hydraulic gradient variation across the interaction zone.

Physicochemical Properties of Water Samples

During field measurements, it became clear that there existed physicochemical differences between the surface water and groundwater environments. Surface water exhibited oxic conditions (DO: 6.8 ± 0.5 mg/L, n=12; redox: +120 ± 15 mV, n=12), while groundwater was suboxic-anoxic (DO: 3.2 ± 0.4 mg/L, n=12; redox: −50 ± 20 mV, n=12) (Table 1 & figure 3).

The pH level in all sampling sites was within the neutral to slightly alkaline range, favoring a variety of microbes. The conductivity of the electric field was always greater in groundwater, which indicated a higher level of dissolution of minerals and a longer period of interaction between water and rocks.

Table 1: Physicochemical characteristics of groundwater and surface water samples.

Parameter	Surface Water (Mean ± SD)	Groundwater (Mean ± SD)
Temperature (°C)	24.5 ± 1.2	22.8 ± 1.0
pH	7.4 ± 0.3	7.6 ± 0.2
Dissolved Oxygen (mg/L)	6.8 ± 0.5	3.2 ± 0.4
Electrical Conductivity (µS/cm)	420 ± 35	780 ± 60
Redox Potential (mV)	120 ± 15	-50 ± 20

Table 1 is a comparative summary of important physicochemical parameters of surface water and groundwater. The surface water shows higher temperatures and a high level of dissolved Oxygen, which is a sign of more active interaction with the atmosphere and aerobic conditions. Groundwater, on the other hand, has greater electrical conductivity and reduced redox potential, implying greater mineral content and an increased reducing (anaerobic) environment. The acidity levels are comparatively stable, as shown by the pH values of both types of water that are close to the neutral range.

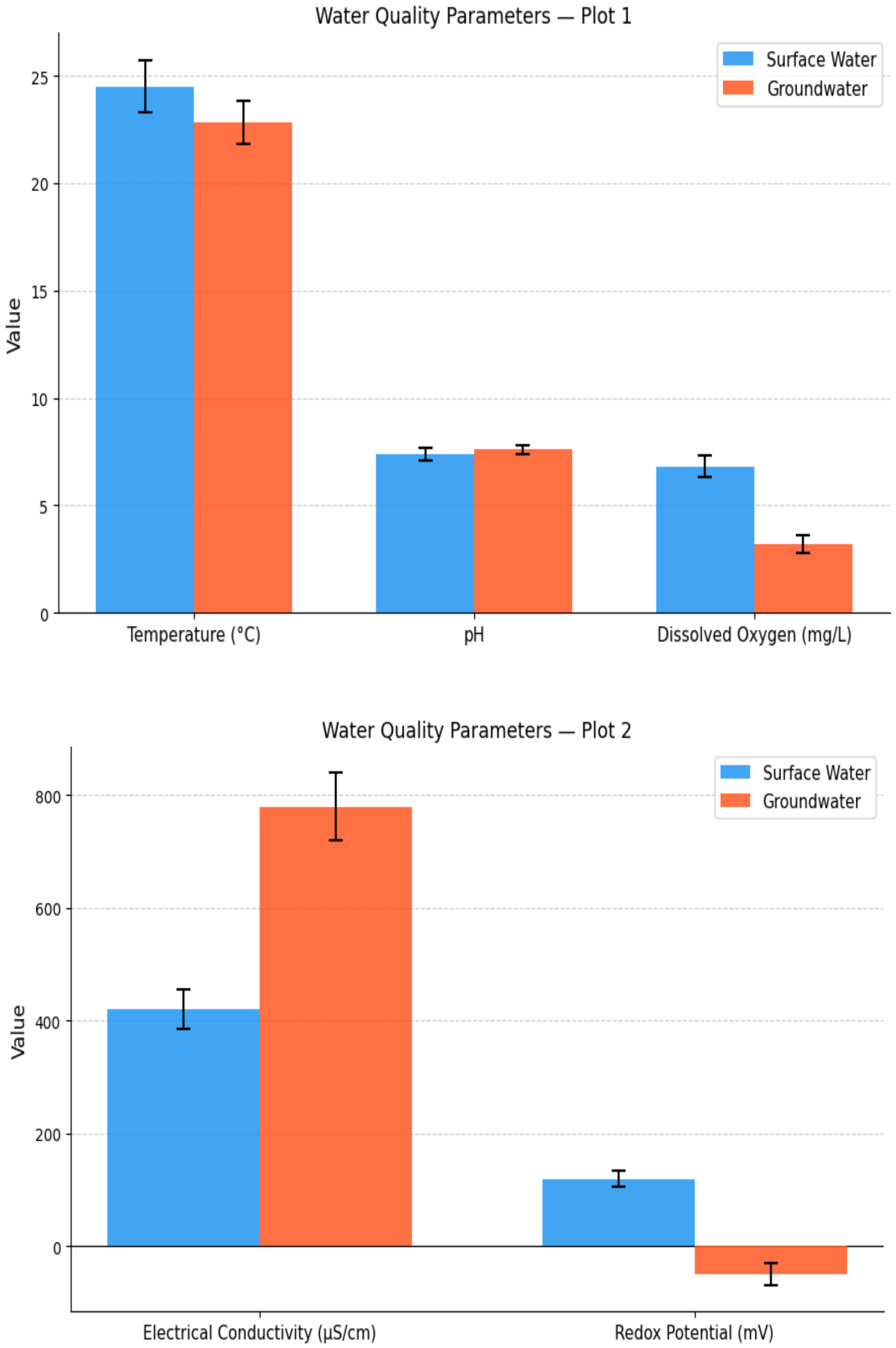

Figure 3: Physicochemical and redox gradient between surface water and groundwater. 3a: variation in temperature, pH, and dissolved oxygen between surface water and groundwater. 3b: contrasting electrical conductivity and redox potential between surface water and groundwater.

Figure 3a. Bar graph of Temperature, pH, and Dissolved Oxygen between surface water and groundwater. Surface water was observed to be relatively high in temperature and dissolved Oxygen as compared to groundwater, and the near-neutral pH of the two kinds of water was comparable. The higher dissolved Oxygen in surface water reflects greater atmospheric interaction and biological activity at the surface. Error bars represent ± one standard deviation.

Figure 3b. Bar plot comparing Electrical Conductivity and Redox Potential between surface water and groundwater. There was significantly higher electrical conductivity of groundwater than surface water, and thus, a higher concentration of dissolved ions as a result of weathering of minerals in the subsurface. The redox potential values indicated the oxidizing conditions in surface waters and reducing conditions in groundwater, as the two water sources had different geochemical environments. Error bars represent ± one standard deviation.

Microbial Community Dynamics

The allocation of operational taxonomic units (OTUs) at the phylum level indicated that Firmicutes and Actinobacteriota were the most common in all the sampling sites with relative abundances of between 28-46 %. A notable proportion of the sequences (12-35%) were not identified, and this suggests that there were under-researched groups of microbes in the subsurface. Other significant phyla were Chloroflexi and Planctomycetota, which were more represented in groundwater samples, and indicated an adaptation to low-oxygen and nutrient-limiting environments.

The microbial communities in the hyporheic zone were more diverse and had compositional overlap with the surface water and groundwater, indicating active mixing and ecological transition. More stable environmental conditions were, however, represented by more specialized anaerobic taxa in deeper groundwater samples. There was a clear change in community composition towards localities nearer to the interface, where greater hydraulic exchange probably raised nutrient levels. These results indicate that hydrological connectivity has a great impact on microbial composition and related biogeochemical reactions.

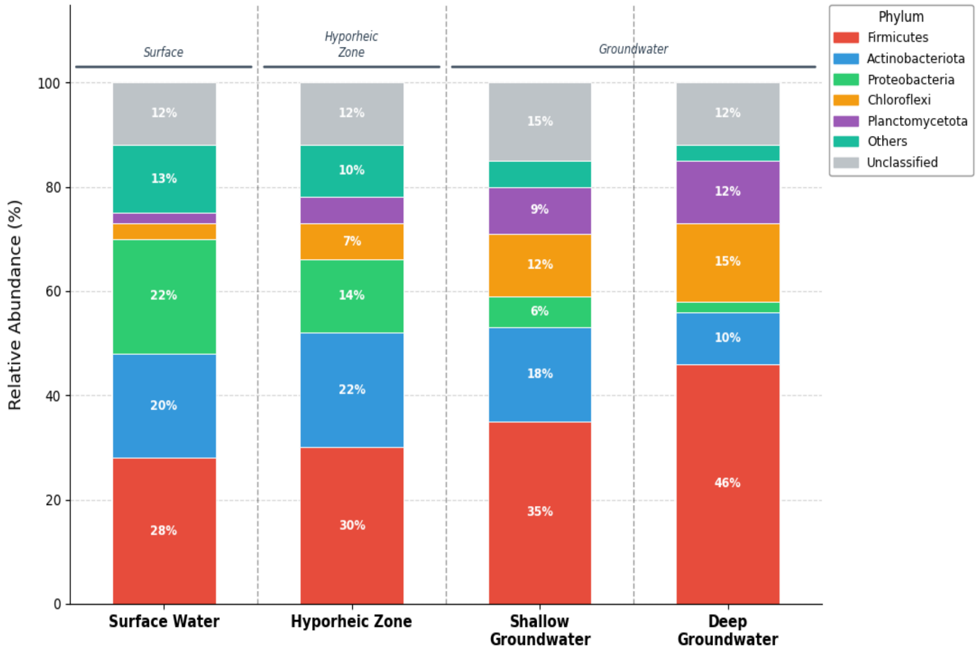

Figure 4: Microbial community composition across surface water, hyporheic zone, and groundwater systems.

Figure 4 shows the relative abundance of the dominant microbial phyla in the various hydrological compartments. The surface water is characterized by the higher percentages of aerobic groups, and the groundwater reflects higher percentages of anaerobic-adapted taxa. The hyporheic zone is characterized by a mixed and diverse community structure and active exchange of hydrological and transitional environmental conditions.

Chemical Composition and Nutrient Dynamics

The chemical analysis indicated that the levels of the nutrients had high gradients across the interface, and there were dynamic transformation processes across the interface. There were high levels of nitrate in surface water and high levels of ammonium in groundwater, thus indicating that nitrification was occurring in the oxic waters and denitrification in the reducing waters was occurring. In groundwater, the phosphate levels were also moderately elevated, which was probably caused by the dissolution of minerals and desorption under the reducing conditions. The dissolved organic carbon was maximum in the hyporheic zone, which means that there is more breakdown by microbes and more production and decomposition of organic matter.

Table 2: Chemical composition of water samples.

Parameter	Surface Water (mg/L)	Groundwater (mg/L)
Nitrate (NO_3^-)	8.5 ± 1.1	3.2 ± 0.8
Ammonium (NH_4^+)	1.2 ± 0.3	4.6 ± 0.9
Phosphate (PO_4^{3-})	0.9 ± 0.2	1.5 ± 0.4
Dissolved Organic Carbon	5.8 ± 0.7	4.2 ± 0.6
Sulfate (SO_4^{2-})	12.4 ± 2.0	18.6 ± 2.5

A comparison of the nutrient levels of surface water and groundwater, with particular emphasis on the chemical properties of the water, is presented in table 2. The nitrate and dissolved organic carbon are found in greater amounts in the surface waters, and this shows that there is biological activity and external contributions like runoffs. On the other hand, groundwater has more ammonium, phosphate, and sulfate, implying poor conditions and dissolution of minerals within the underworld. These differences can be attributed to the fact that there is a difference in the biogeochemical processes and the nutrient cycling in the two water systems.

Solute Transport and Reaction Processes

Application of the advection dispersion model revealed that the movement of the solutes is greatly influenced by the flow velocity and dispersion. The regions with greater flow velocities were transporting solutes at a greater rate, and those with lower velocity had longer residence time, which enhanced microbial degradation and chemical reactions. The nutrient removal in reaction terms was high, with the removal of nitrate in the low-oxygen areas being the most significant.

Hydrological and Geochemical Modeling Outcomes

There was a good correspondence between the hydrological and geochemical model simulation and field data. Flow modeling in Darcy affirmed the direction of the flow of groundwater and the contribution of the surface water flow. Geochemical model demonstrated that redox reactions, mineral dissolution, and microbial processes are not only significant regulators of the chemistry of the interaction zone but also important.

Statistical Relationships and Data Integration

Multivariate statistical analysis revealed that there were unique relationships between the microbial communities and the environmental variables across the interaction zone. Parameters like redox potential and dissolved Oxygen started to contribute to the determination of the distribution of microbes, which suggests that oxic and anoxic environments are parameters of relevance in the determination of the community structure. The principal component analysis also revealed that the high variation in the data was largely attributed to the availability of nutrients and hydrology. These trends suggest that geochemical gradients and flow processes can play a significant role in controlling the microbial makeup and activity of the system.

Discussion

The study has shown that there is good surface water interconnection of groundwater with a hydraulic gradient ranging between 0.002 and 0.015, which indicates the spatial variation of gaining and losing conditions. Surface water (DO: 6.8 mg/L; redox: +120 mV) and groundwater (DO: 3.2 mg/L; redox: −50 mV) were found to be suboxic and anoxic, respectively. The conductivity was much greater in the groundwater (780 µS/cm) compared to surface water (420 µS/cm). Firmicutes and Actinobacteriota (28-46% maximum in the hyporheic zone) dominated the microbial communities. The nutrient gradients showed that the surface water contained a high concentration of nitrate (8.5 mg/L) and groundwater contained a high concentration of ammonium (4.6 mg/L), which indicated active changes of nitrogen. The interconnected hydrological and biogeochemical processes are seen to control the patterns. Hydraulic gradients can cause advectional flow according to the law of Darcy, whereby the steeper the gradient, the more rapidly the water in the pore's flows, and the faster the solutes will move, but the lower the residence time the microbes have to be processed. Low-gradient zones, on the other hand, allow longer residence times, which can be transported by diffusion and react by microbiological mechanisms. The robust redox stratification is due to the different availability of Oxygen. The aerobic metabolism and the nitrification (reduction of NH_4^+ to NO_3^-) are supported by constant exchange with the atmosphere in order to maintain oxic conditions in the surface water. Conversely, when oxygen in groundwater is depleted, other electron acceptors (e.g., NO_3^-, SO_4^{2-}) are encouraged to induce denitrification and sulfate reduction. This is why there is a build-up of ammonium and reduced species in groundwater. The hyporheic zone is a dynamic mixing interface where changing redox, nutrient inflow, and organic carbon environments promote microbial diversity and physiological versatility. The high dissolved organic carbon in this zone is a source of energy and increases the heterotrophic action and speeds up the process of recycling of nutrients. The long-term interaction of water and rock increases the electrical conductivity of groundwater as it leads to better dissolution and release of minerals.

H1 (microbial control over the transformations) was accepted: PCA (PC1=48.2% variance; eigenvalues >1.5) indicated redox/DO (loadings 0.82, 0.79) explained 62% of microbial variance (PERMANOVA: F=4.6, p=0.001). MLR: microbial diversity ~ DO + NO_3^- (R^2=0.71, β_DO=0.45, p<0.01, n=24). These findings highlight that the groundwater-surface water interface is an important biogeochemical reactor regulating nutrient transformation, particularly the nitrogen cycle. The flow dynamics and redox conditions are interrelated to regulate the contaminant attenuation and ecosystem health. These systems play a vital role in the purification of natural water, particularly in regions with the influence of monsoon, where seasonal hydrologic changes enhance exchange processes. Discrete sampling (biweekly, n=6 campaigns, May-Oct 2025) failed to capture the diurnal variability (estimated less than 10% DO variability in literature); 12-35% unclassified OTUs constrained functional prediction (handled by PICRUSt2 in future work). Models were assumed homogeneous K (variability ±20%; sensitivity tested). The presence of a high proportion of unclear microbial taxa discourages functional interpretation. Also, complex subsurface heterogeneity and reaction kinetics can be simplified by model assumptions of homogeneity. Further research should combine high-resolution time-resolved monitoring with more advanced techniques such as metagenomics and isotopic labeling to allow a direct relationship between microbial identity and functionality. Coupled reactive transport modeling would be added to the predictive capability, and microbial kinetics would be added. The further development of studies in different hydrogeological environments will help to understand better the universal and site-specific controls on the interaction between groundwater and surface water.

Conclusion

In this paper, the complex interactions that occur between the groundwater surface water interface were addressed, and how the combination of hydrological connectivity, physicochemical gradients, and microbial processes collectively controls the processes of nutrient cycling and solute transport. This was to learn about the processes that control water quality and biogeochemical changes in this dynamic transition zone. The results affirm high hydraulic connectivity, with gradients between 0.002 and 0.015, that drive spatially varying gaining and losing conditions. Dissolved Oxygen in the surface water (6.8 mg/L) was found to be higher than in the groundwater (3.2 mg/L), and the electrical conductivity was also higher in groundwater (780 µS/cm versus 420 µS/cm). There was a strong redox gradient (+120 mV to −50 mV) that controlled microbial activities. The Firmicutes and Actinobacteriota (28-46%), dominated microbial communities, and the hyporheic zone had increased diversity. The nutrient dynamics indicated that there were active nitrification and denitrification since nitrate levels were higher in the surface water (8.5mg/L) and ammonium in groundwater (4.6mg/L). In general, the paper indicates that the interaction zone is a coupled hydrological-biogeochemical system in which the dynamics of flow influence the residence time, redox conditions, and microbial activity. The hyporheic zone becomes a hotspot of nutrient conversion and exchange of life. Such interfaces are vital in water quality control and stability of ecosystems, according to these findings. The next wave of research should seek to integrate high-resolution time-scale observation, advanced molecular analysis, and a reactive transport model to make sure that the system captures more detail. The predictive insights may be extended to even greater depths with further expanded research in all environmental settings, but this will additionally aid in the sustainable control of water resources.

Ethical and Environmental Considerations

Field research is done with the least ecological disturbance, and all the necessary permissions are obtained. The environmental regulations are followed, so as to carry out research in a sustainable and responsible way.

References

Das, A., 2025. Prediction of Urban Surface Water Quality Scenarios Using Water Quality Index (WQI), Multivariate Techniques, and Machine Learning (ML) models in water resources, in Baitarani river basin, odisha: potential benefits and associated challenges. *Earth Systems and Environment*, pp.1-37. https://doi.org/10.1007/s41748-025-00623-0

Fleckenstein, J.H., Krause, S., Hannah, D.M. and Boano, F., 2010. Groundwater-surface water interactions: New methods and models to improve understanding of processes and dynamics. *Advances in Water Resources*, *33*(11), pp.1291-1295. https://doi.org/10.1016/j.advwatres.2010.09.011

Fu, C., Xu, B., Chen, H., Zhao, X., Li, G., Zheng, Y., Qiu, W., Zheng, C., Duan, L. and Wang, W., 2022. Occurrence and distribution of antibiotics in groundwater, surface water, and sediment in Xiong'an New Area, China, and their relationship with antibiotic resistance genes. *Science of the Total Environment*, *807*, p.151011. https://doi.org/10.1016/j.scitotenv.2021.151011

Gaur, N., Sarkar, A., Dutta, D., Gogoi, B.J., Dubey, R. and Dwivedi, S.K., 2022. Evaluation of water quality index and geochemical characteristics of surfacewater from Tawang India. *Scientific Reports*, *12*(1), p.11698. https://doi.org/10.1038/s41598-022-14760-3

Krause, S., Lewandowski, J., Grimm, N.B., Hannah, D.M., Pinay, G., McDonald, K., Martí, E., Argerich, A., Pfister, L., Klaus, J. and Battin, T., 2024. Ecohydrological interfaces as hotspots of ecosystem processes. *Ecohydrological Interfaces*, pp.1-28. https://doi.org/10.1002/9781119489702.ch1

Larned, S.T., Gooseff, M.N., Packman, A.I., Rugel, K. and Wondzell, S.M., 2015. Groundwater–surface-water interactions: current research directions. *Freshwater Science*, *34*(1), pp.92-98. https://doi.org/10.1086/679491

Lee, J.H., Lee, B.J. and Unno, T., 2018. Bacterial communities in ground-and surface water mixing zone induced by seasonal heavy extraction of groundwater. *Geomicrobiology Journal*, *35*(9), pp.768-774. https://doi.org/10.1080/01490451.2018.1468834

Lewandowski, J., Meinikmann, K. and Krause, S., 2020. Groundwater–surface water interactions: Recent advances and interdisciplinary challenges. *Water*, *12*(1), p.296. https://doi.org/10.3390/w12010296

Li, C., Gao, X., Wang, W., Zhang, X., Zhang, X., Jiang, C. and Wang, Y., 2021. Hydro-biogeochemical processes of surface water leakage into groundwater in large scale karst water system: A case study at Jinci, northern China. *Journal of Hydrology*, *596*, p.125691. https://doi.org/10.1016/j.jhydrol.2020.125691

Li, J., Zhu, D., Zhang, S., Yang, G., Zhao, Y., Zhou, C., Lin, Y. and Zou, S., 2022. Application of the hydrochemistry, stable isotopes and MixSIAR model to identify nitrate sources and transformations in surface water and groundwater of an intensive agricultural karst wetland in Guilin, China. *Ecotoxicology and Environmental Safety*, *231*, p.113205. https://doi.org/10.1016/j.ecoenv.2022.113205

Liang, W., Chen, X., Zhao, C., Li, L. and He, D., 2023. Seasonal changes of dissolved organic matter chemistry and its linkage with greenhouse gas emissions in saltmarsh surface water and porewater interactions. *Water Research*, *245*, p.120582. https://doi.org/10.1016/j.watres.2023.120582

Mladenov, N., Parsons, D., Kinoshita, A.M., Pinongcos, F., Mueller, M., Garcia, D., Lipson, D.A., Grijalva, L.M. and Zink, T.A., 2022. Groundwater-surface water interactions and flux of organic matter and nutrients in an urban, Mediterranean stream. *Science of The Total Environment*, *811*, p.152379. https://doi.org/10.1016/j.scitotenv.2021.152379

Modie, L.T., Kenabatho, P.K., Stephens, M. and Mosekiemang, T., 2022. Investigating groundwater and surface water interactions using stable isotopes and hydrochemistry in the Notwane River Catchment, South East Botswana. *Journal of Hydrology: Regional Studies*, *40*, p.101014. https://doi.org/10.1016/j.ejrh.2022.101014

Ottosen, C.B., Rønde, V., McKnight, U.S., Annable, M.D., Broholm, M.M., Devlin, J.F. and Bjerg, P.L., 2020. Natural attenuation of a chlorinated ethene plume discharging to a stream: Integrated assessment of hydrogeological, chemical and microbial interactions. *Water research*, *186*, p.116332. https://doi.org/10.1016/j.watres.2020.116332

Tokranov, A.K., LeBlanc, D.R., Pickard, H.M., Ruyle, B.J., Barber, L.B., Hull, R.B., Sunderland, E.M. and Vecitis, C.D., 2021. Surface-water/groundwater boundaries affect seasonal PFAS concentrations and PFAA precursor transformations. *Environmental Science: Processes & Impacts*, *23*(12), pp.1893-1905. https://doi.org/10.1039/d1em00329a

Tripathi, M., Yadav, P.K., Chahar, B.R. and Dietrich, P., 2021. A review on groundwater–surface water interaction highlighting the significance of streambed and aquifer properties on the exchanging flux. *Environmental Earth Sciences*, *80*(17), p.604. https://doi.org/10.1007/s12665-021-09897-9

Wang, H., Jiao, Y., Hu, B.X., Li, F. and Li, D., 2023. Study on interaction between surface water and groundwater in typical reach of Xiaoqing river based on WEP-L model. *Water*, *15*(3), p.492. https://doi.org/10.3390/w15030492

Yan, A., Guo, X., Hu, D. and Chen, X., 2022. Reactive transport of NH4+ in the hyporheic zone from the ground water to the surface water. *Water*, *14*(8), p.1237. https://doi.org/10.3390/w14081237

Yuan, R., Wang, M., Wang, S. and Song, X., 2020. Water transfer imposes hydrochemical impacts on groundwater by altering the interaction of groundwater and surface water. *Journal of Hydrology*, *583*, p.124617. https://doi.org/10.1016/j.jhydrol.2020.124617

Zhu, A., Yang, Z., Liang, Z., Gao, L., Li, R., Hou, L., Li, S., Xie, Z., Wu, Y., Chen, J. and Cao, L., 2020. Integrating hydrochemical and biological approaches to investigate the surface water and groundwater interactions in the hyporheic zone of the Liuxi River basin, southern China. *Journal of Hydrology*, *583*, p.124622. https://doi.org/10.1016/j.jhydrol.2020.124622