Environmental Sustainability (2024) 7:121–133
https://doi.org/10.1007/s42398-023-00290-9

REVIEW

Intensification of contaminants, hydrology, and pollution of hyporheic zone: the liver of river ecology—a review

Lone Rafiya Majeed[1] · Lone Fawad Majeed[2] · Sumaira Rashid[3] · Sartaj Ahmad Bhat[4] · Narendra Kumar[5] · Vineet Kumar[6]

Received: 19 January 2023 / Revised: 12 September 2023 / Accepted: 28 September 2023 / Published online: 31 October 2023

Abstract

The ecological activities within the hyporheic zone (HZ) heavily rely on water flow dynamics. The arrangement of the hyporheic community is influenced significantly by the hydrological fluxes occurring within the zone, particularly driven by the dynamics of watercourse surface flow. While there is an ongoing debate, it is suggested that benthic organisms may utilize the HZ as a sanctuary. The ability of stream organisms to colonize the HZ is influenced by their biological characteristics. Lower oxygen levels and reduced pore space in deeper sediment layers restrict the presence of macroinvertebrates while favoring meiofauna and protists. Limited research has been conducted on the overall role of hyporheos in the assembly of entire ecosystems, with most studies focusing on larger species. The metabolism of the hyporheos facilitates the transformation of pollutants and nutrients within the HZ through the action of biofilms that degrade dissolved substances, including contaminants. Lastly, the community that feeds on biofilms and participates in hyporheic exchange flow indirectly contributes to these processes. The aim of this review article is to highlight the critical role of water flow dynamics in the hyporheic zone and its influence on the arrangement of the ecological community within. It emphasizes the potential sanctuary function of the hyporheic zone for benthic organisms, shaped by their biological characteristics.

Keywords Hyporheic exchange · Hydrological fluxes · Benthic · Biofilms · Environmental pollution

✉ Vineet Kumar
drvineet.micro@gmail.com

[1] Vivekananda Global University, Jaipur 303905, India

[2] Department of Nanotechnology, University of Kashmir, Srinagar, Jammu & Kashmir 190006, India

[3] Department of Environmental Science, University of Kashmir, Srinagar, Jammu & Kashmir 190006, India

[4] River Basin Research Center, Gifu University, 1-1 Yanagido, Gifu 501-1193, Japan

[5] Depatment of Environmental Science, School of Earth and Environmental Science, Babasaheb Bhimarao Ambedkar (A Central) University, Vidya Vihar, Raebareli Road, Lucknow 226025, India

[6] Department of Microbiology, School of Life Sciences, Central University of Rajasthan, Ajmer, Kishangarh, Rajasthan 305817, India

Introduction

The hyporheic zone (HZ) represents a critical interface where surface water and groundwater intermingle, playing a pivotal role in the nutrient cycling and contaminant attenuation processes within river ecosystems (Biehler et al. 2020). Within this zone, sediment filters can act as a means of removing contaminants from rivers or groundwater, while microbial communities carry out direct or indirect activities to metabolize and transform these substances (Yang et al. 2020). In freshwater ecosystems, the sediments at the bottom serve as a connection between the water near the surface of the open channel and the underground water table (Biehler et al. 2020) Consequently, there exists a bidirectional flow along the stream and river continuum, where groundwater is absorbed into the surface water system and vice versa (Bencala et al. 2011). The convergence points of surface and groundwater are referred to as the HZ (Costanzo et al. 2005). Researchers from diverse fields have looked at how the HZ functions within the larger river ecosystem, resulting in the absence of a singular, all-encompassing definition for the HZ. The study of hyporheic processes has long served as a defining characteristic of the field as shown in Table 1 (Gomes and Wai 2019). Various definitions of the HZ exist depending on the discipline: in geochemistry, it pertains to the sediment area containing a proportion of water on the surface, while in biological science, it refers to the capacity of sediments harbouring a given population of the aquatic community (Buffington and Tonina 2009). These definitional and scope-related differences have significant implications. However, a more comprehensive and interdisciplinary definition has been recommended by Ward (2016) (Table 1). From this description of the HZ, it becomes evident that the timescale at which these events occur is crucial. Indeed, the dynamics of the surface water flow greatly influence the flow direction and exchange rate with HZ, with seasonal changes having a particularly pronounced effect. Seasonality can induce a cascade of dramatic shifts in water flow conditions, independent of river dynamics (Gasith and Resh 1999), ultimately determining the position and size of the HZ (Singer et al. 2013). Nonetheless, the HZ mitigates the severity of this variations, making it a more favourable habitat for riverine biota during challenging time (Yu et al. 2020). These seasonal fluctuations have profound implications for shifts in species diversity and abundance (Stubbington 2012). The rich and dynamic populations within the HZ are significantly influenced by the whirling and quantitative possessions of hydrological flows in both position and configuration (Boulton et al. 1998). These hyporheic communities, also known as hyporheos, comprises micro-organisms (primarily fungi and bacteria) that form biofilms, and protists, and invertebrates. Biodiversity and colonisation have a direct impact on the secondary production budget and biomass of the HZ. The HZ is both a biogeochemical and mechanical filter, regulated by water flow and sediment pore space (Boulton 2000; Ren et al. 2023). This zone possesses remarkable self-purification capabilities purification (Lewandowski and Nützmann 2010), ensuring the protection of aquifers (Huang and Yang 2022). Aquifers are vital for providing humans with safe drinking water. Consequently, the headwater zone of rivers and streams plays a vital role

Table 1 Various definitions of the hyporheic zone exist depending on the discipline

Term	Definition	Source
HZ-Original definition	The space between a stream's surface water and its actual groundwater, where various forms of life can thrive	Buffington and Tonina (2009)
HZ-Geological view	Quantity of surface-water-bearing sediments inside a given volume	
HZ-Hydrological view	The area of a streambed that allows water to move from the open channel to the groundwater below it because of pressure differences and water's ability to flow	
HZ-Biological view	The area of a streambed that allows water to move from the open channel to the groundwater below it as a result of pressure gradients and hydraulic conductivity	
HZ-Integrative definition	Anyplace that satisfies these four requirements; To completely saturate the surface, The existence of a flow channel that begins in surface water and terminates back there is required for the timescales at which processes of interest Interact with the stream are those that are important to those studies From the subsoil to the groundwater continuum, interesting processes occur continually	Ward (2016)
Hyporheos	Biological communities found in a stream's saturating interstitial areas (benthic zone)	Stanley and Boulton (1993)
Upwelling (UW) zone	Some parts of the riverbed have more pressure than others, and this is where the surface water leaves the HZ and flows into the open channel	Franken et al. (2001)
Downwelling (DW) zone	Those low spots in the riverbed where the HZ meets the surface water	
Hyporheic exchange flows	The HZ's water mass that permeates the sediment pore spaces is amplified and steered by the alternating UW and DW zones	
Micropollutants	Trace amounts of numerous new contaminants (such as medications, personal care items, steroid hormones, industrial chemicals, and pesticides) are widespread in our waters. These quantities can range from a few nanograms per litre to several 114 milligrammes per litre	Luo et al. (2022)
Hyporheic bioreactor	To put it simply, hyporheic systems are biologically active systems in which chemical molecules are altered as a result of the actions of hyporheic organisms or the active chemicals they produce	Lewandowski and Nützmann (2010)
Residence time	Solutes dissolved in water are subject to biogeochemical transformations during the period of their hydrodynamic retention in the HZ	Biehler et al. (2020)

in biomass and energy redistribution, nutrient recovery, and pollution prevention (Tewari et al. 2022). The headwater zone of rivers and streams reduces concentrations of nitrogen, phosphorus, and organic carbon (Akhtar et al. 2022). The fate and elimination rates of emerging micropollutants in lotic systems (Table 1) remain largely unknown (Zhou and Endreny 2013), making it unclear how these molecules interact with the bioreactor. This unresolved subject is of fundamental importance in ecology. One can draw parallels between the hyporheic bioreactor and the "liver" of a river (Krause et al. 2009; Krause et al. 2009). Besides its role in the creation, exchange, metabolism, and modification of dissolved chemicals, the HZ also significantly impacts the overall ecosystem condition. This paper examines the interrelationships among hyporheic exchange flow, community ecosystem, and the reduction of contaminants in the HZ (Zhou and Endreny 2013). While distinct research projects have investigated these questions and concerns individually, it is essential for all of them to be interconnected for the effective functioning of the hyporheic bioreactor.

Methodology for literature survey

The initial stepS involved defining the research question and determining the scope of the literature review. In this case, the research question is "How does the HZ attenuate contaminants, and what role do hydrology, community ecology, and pollution play in this process?" Subsequently, a list of keywords and search terms relevant to the research question were developed. Examples of these search terms include "HZ", "contaminants", "pollution", "hydrology", "community ecology", and "attenuation". Using these search terms, we conducted comprehensive literature searches utilizing academic databases, such as Web of Science, Google Scholar, and Scopus. Additionally, reviewing the bibliographies of relevant articles provided further sources. Upon compiling a list of pertinent studies, we shortlisted the titles and abstracts that were relevant to the topic and discarded irrelevant ones. Relevant information from the selected articles was carefully noted and comprehensively analyzed. Finally, a conclusion was drawn, and a flowchart representing future research prospects in the field was created (Fig. 1).

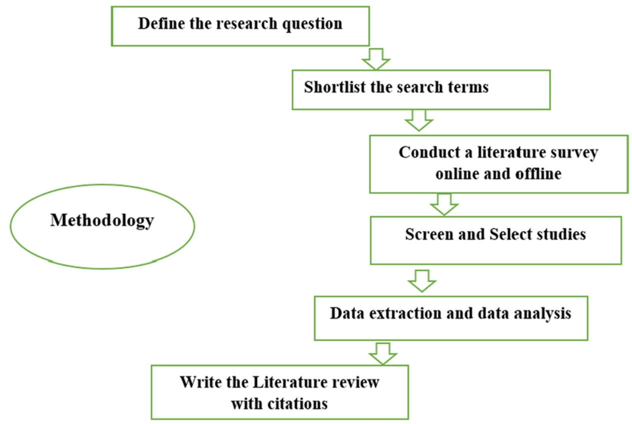

Fig. 1 Methdology followed for litrature survey

Features of hypophoric zone

Hydrology

In most cases, the majority of baseflow in streams is derived from subterranean water sources although there are exceptions (Son et al. 2022). The HZ acts as the interface between groundwater and surface water, facilitating bidirectional water flow between the stream and sediment at the stream-sediment boundary, provided that porous sediments allow fluid albeit with dispersed flow patterns (DelVecchia et al. 2022).

Slight pressure differentials between subsurface and surface water give rise to upwelling and downwelling zones, where groundwater flows into the stream and surface water enters the HZ (Arora and Misra 2022). The size of these zones can vary from a few square centimetres to kilometres (Reidy and Clinton 2004), although they are typically small (Dole-Olivier et al. 2022). Due to the steady-state nature of stream discharge, hyporheic flow is more likely to occur in the central part of the streambed. Within the subsurface, the residency time is shorter along the stream's edges and longer in its middle (Kaiser 2022). Discharging zones typically dominate most stream reaches, however, continuous up and down flows become more frequent downstream (Conant Jr 2004). Stream flows can also occur longitudinally or laterally along the bankside. Slight differences in elevation above the groundwater level in a stream create flows in one direction (Marciniak et al. 2022). Groundwater discharges and head-driven inflows are often observed near the head of pools and the foot of riffles, which are characteristic of steady-state flows shown in Fig. 2. However, transient changes in the water environment, such as rainfall, snowmelt, major floods, and dam releases, can generate significant spatial variations (Boano et al. 2009).

Longitudinal flows can be initiated by advective pumping, where groundwater meets surface water at the upstream faces of bedforms due to flow-driven pressure differences (Liang et al. 2022). This phenomenon, initially described analytically by Vaux (1968) is known to enhance exchange rates without altering the head differences between surface and subsurface water (Mendoza-Lera et al. 2019). In the absence of bedform relief, turbulence can potentially induce hyporheic exchange (Packman et al. 2004). However,

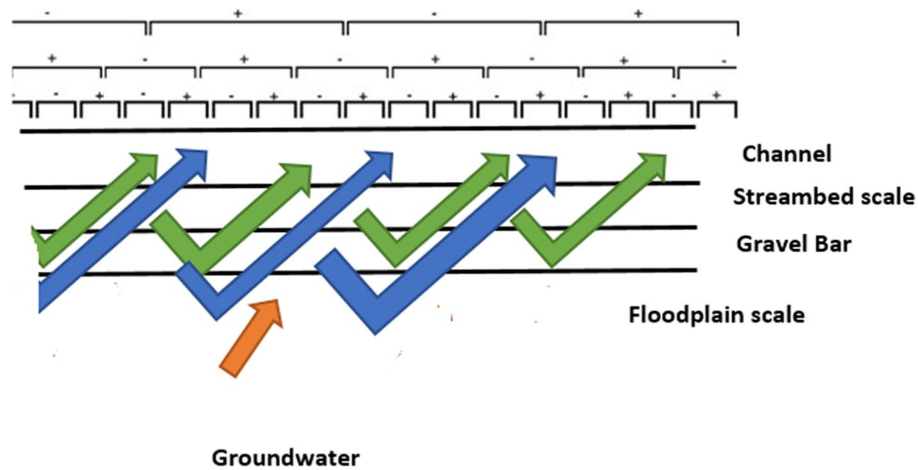

Fig. 2 Subsurface flow paths vary from seconds to minutes to months to years (modified from Poole et al. 2008). Subsurface pathways are longer when temporally longer. Groundwater directs flow

bedform conditions may be transient due to the constant reshaping of the bed sediment (Stubbington 2012).

Lateral flows within HZs can be attributed to various factors, including temporary water level fluctuations (bank storage), paleochannels across floodplains, meandering with varying degrees of head, riffle-pool sequences, and channel sinuosity (Bruno et al. 2009). While less attention has been given to lateral flows compared to longitudinal flows, studies have demonstrated that meander-driven flows are the most significant (Torgeson et al. 2022) with the highest flows occurring at hinge points and persisting even under high groundwater discharge rates. Asymmetrical point bar drifts are initiated by channel sinuosity (Cardenas 2008), and horizontal flow rates can range from 1 cm per day to 43 m per day. Poole et al. (2008) have observed substantial flow parallel to stream channels in alluvial aquifers.

Geochemistry

Surface-subsurface interactions have a profound impact on stream characteristics, particularly in terms of geochemistry (Fang et al. 2020). Redox reactions, involving the reduction and oxidation of molecules, play a critical role in these interactions. In biologically active systems, these reactions often involve carbon (C) (Iepure et al. 2022). Oxygen (O_2) is the most common electron acceptor in the environment, while other compounds lacking O_2 serve as terminal electron donors. As the redox potential decreases, electron acceptors are thermodynamically favored in the following order: nitrate to dinitrogen/ammonia; manganese valence state declines from 4 to 2, and iron valence state decreases from 3 to 2; sulfates to sulfides; and carbon dioxide to methane (Yan et al. 2022). Groundwater in surface flow systems generally contains insufficient dissolved organic C to sustain significant metabolism that consumes large amounts of O_2 over short periods. Therefore, groundwater is typically well-oxygenated (Poole et al. 2022). Only older groundwater with deeper and longer flow paths could be anoxic and support redox reactions with terminal electron acceptors other than O_2 (Huang and Yang 2022). Surface water is typically oxygen rich (Robertson and Wood 2010a). However, areas with reduced dissolved oxygen (DO) can occur in surface water behind dams or in channels and backwaters where organic matter accumulates and water advection is limited (Michaelis et al. 2022). Hyporheic flow pathways encounter sufficient C to support respiration, leading to a decrease in subsurface oxygen (Dwivedi 2019), and oxygen levels decline with residence time in the HZ (Ahmed and Srinivasa Rao 2015). Upwelling water has much lower DO than downwelling water due to increased groundwater intrusion. The nutrient dynamics of streams are primarily influenced by the HZ due to its location (Lapham et al. 2021). The HZ serves as a transitional area between open water and sediment conditions. It is characterized by fluctuating electron donors and acceptors within a patchy mosaic, creating the impression of water cycling in and out of the zone. Baker (2000) found that these parameters significantly affected the chemical composition of streams. Due to the occurrence of a redox gradient linked with DO depletion, the HZ is considered a geochemical hotspot. This gradient promotes chemical transformations, particularly denitrification (Yan et al. 2022). The production of carbon dioxide as a byproduct of respiration leads to pH values in the HZ that differ from those of the groundwater and the stream. Other interactions, many of which are amplified by the connection between sediment and water, can also alter the surrounding pH (Runkel 2007). According to the research conducted by Cooper et al. (2022), reaction sites shift in response to changes in subsurface flows caused by groundwater or stream movements. If flow alterations are driven by seasonal patterns, such as floods, droughts, or precipitation, then these changes are likely to be predictable (Nelson et al. 2019) .

Biology

Biological factors, such as populations of hyporheic-dependent invertebrates, are often given high priority by stream remediation project managers. The HZ is renowned for its significant biological characteristics, serving as a refuge for disturbed invertebrates and a prime incubation site for stream fauna (Milner et al. 2022). Stream invertebrates seek shelter in the HZ, which provides a more stable environment compared to open waters, thanks to reduced water velocity and more constant temperatures. Temperature, as indicated by Banks et al. (2019) plays a crucial role in HZ processes. Deeper waters exhibit less temperature variability than surface waters. Over short time scales, night-time lows increase and daytime highs decrease, while over mitigating daily or seasonal temperature fluctuations, hyporheic flows equilibrate with groundwater temperatures, and longer flow paths, (Poole et al. 2008). Consequently, the intermittent pulses of water from HZ help regulate stream water temperatures. Researchers have utilized temperature variations in the stream to measure hyporheic exchange rates (Hübner et al. 2020). The presence of stable subsurface temperatures in upwelling zones is beneficial for the spawning of salmonids (van Grinsven et al. 2015).

Recovery of benthic populations takes longer after major floods (Maier and Howard 2011), primarily because organisms seeking refuge in downwelling areas assist in the rapid recovery of benthic dwellers (Guo and Jiang 2020). According to Stubbington (2012), determining which organisms seek refuge where and when is possible is not consistent. The efficacy of the refuge depends on sediment type, taxa, type of disturbance, and whether the response to the disturbance is passive or active (Lorenzo et al. 2021). Robertson and Wood (2010a) suggest that certain disturbance events have the potential to alter the hyporheic environment and refuge functions. The HZ is composed of a patchwork of various small habitats due to sediments, water flows, and prevailing conditions (Sackett et al. 2019). Upwelling groundwater in close proximity (possibly associated with finer sediments of the pool) and other sediments and flows related to meander erosion all contribute to the benthic sediment pattern of a river (Boulton 2007). Benthic sediment patterns can also be associated with meander erosion (Langenhoff et al. 2013).

Microbes, meiofauna, and macrofauna are all organisms that can be found in the HZ (Mermillod-Blondin et al. 2013). Faunal characterizations of the HZ are dominated by insect instars, which are transient members of ecosystem (Boulton et al. 2010). The HZ is known to harbor aquatic insect juveniles, water mites, flatworms, rotifers, segmented worms, and, hyporheos crabs, as identified by various biologists (Graham et al. 2022). Management programs for the HZ often focus on salmonid fish eggs and alevin, which inhabit excavated redds that are subsequently refilled by adults. DO affects the overall distribution of hyporheos organisms (Kasahara et al. 2022), along with grain proportions and vertical flow arrangements (Olsen and Townsend 2003).

Biofilms in the HZ are formed by HZ bacteria. According to Storey et al. (2003) biofilms create microenvironments, which are small anaerobic zones within oxygenated environments. These zones are crucial for denitrification. However, the supply of nutrients and waste in biofilms is controlled by advected waters (Sobczak and Findlay 2002). This is due to the presence of expressed enzymes and limited pore space, which create highly specialized environments within biofilms.

Hyporheic hydrodynamics drives hyporheic zone ecology

According to Gomez-Velez and Harvey (2014) there is a continuous, bidirectional interchange of energy and water between the primary channel of the river and the surrounding sediments at the sediment water interface (SWI). This interchange plays a significant role in biogeochemical cycling, stream heat regulation, and ecological functioning along river corridors (Hannah et al. 2009; Harvey and Gooseff 2015; Vonk et al. 2019). A comprehensive understanding of dynamic hyporheic processes requires insights of the interactions among drivers and controls of exchange (see Fig. 3; Gomez-Velez and Harvey 2014). These interactions include dynamic forces in sediment transport, sediment hydraulic conductivity and porosity, morphometry, and slope. The complex interactions and exchange mechanisms not only affect the scale of hyporheic exchange flux (HEF), but also influence the residence time of water and solutes on the streambed and the formation of stagnation zones. Singh et al. (2020) found that the extent and depth of streambed exposed to these processes are also impacted. Hyporheic exchange occurs across a wide array of temporal and spatial scales, which are determined by factors such as channel geometry, slope, and landscape characteristics of the streambed (Boano et al. 2009). Additionally, sediment hydraulic properties and their heterogeneity, along with ambient groundwater flow, influence the exchange process (Cardenas et al. 2004; Gomez-Velez and Harvey 2014).

The influence of seasonal fluctuations in river flow on the communities

There have been extensive studies on the HZ over the last three decades, particularly focusing on steady-state flow conditions (Buffington and Tonina 2009). However, researchers are only just beginning to comprehend the significance of ephemerality in-stream flow (Boano et al.

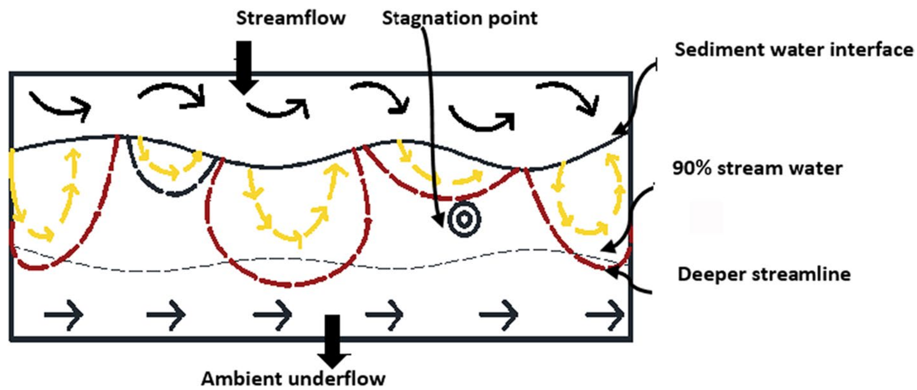

Fig. 3 Hyporheic hydrodynamics driving hyporheic zone ecology

2007; Gomez-Velez et al. 2017). Hydropeaking and thermal peaking can occur due to regular variations in rainfall, evapotranspiration, and snowmelt, as well as human activities, like wastewater treatment and dam operations. Peak flow events lead to increased downwelling surface water, which is richer in essential nutrients and oxygen, consequently impacting biogeochemical processes in the streambed, including denitrification, nitrification, anaerobic and aerobic carbon respiration (Fritz et al. 2008; Trauth and Fleckenstein 2017). These effects can potentially extend to greater depths and larger streambed areas (Bruno et al. 2009). Therefore, stream stage and flow have significant implications for hyporheic and benthic invertebrates, thermal conditions, and nutrient cycling (Bruno et al. 2020).

Recent findings have highlighted the significance of understanding the dynamic environment of river corridors (Dudley-Southern and Binley 2015; McCallum and Shanafield 2016; Malzone et al. 2016; Schmadel et al. 2016; Gomez-Velez et al. 2017; Trauth and Fleckenstein 2017; Bruno et al. 2020). Ward et al. (2018) have identified key drivers and controls of hyporheic exchange flows during transient stream flow conditions. Several studies have demonstrated the significance of hillslope lag, hillslope amplitude, cross-valley and down-valley slopes in determining hyporheic flow paths and residence times (Malzone et al. 2016; Schmadel et al. 2016). Graham et al. (2022) observed changes in inflow and outflow residence time patterns for various discharge events. Peak discharge and event duration play a crucial role in determining the mean age of water and solutes, which in turn affects rates of anaerobic and aerobic respiration. In a study, Gomez-Velez et al. (2017) employed a dimensionality-free framework to investigate the relationship between flow characteristics, the spatial and temporal progression of riverbank storage, and sinuosity-driven hyporheic exchange. However, hydrological and geomorphological controls on hyporheic exchange flows with biogeochemical implications have not been thoroughly addressed in previous dynamic studies.

River budgeting, stream biota, and productivity utilising the hyporheic zone

Determining system limitations is crucial for analyzing ecological processes (Fudyma et al. 2021). When studying stream and river, the three classic spatial compartments considered are the benthic zone, the open channel, and the headwater zone (H–Z) or riparian zone. Measuring secondary production allows for the quantification of the flux of energy output (in the form of biomass) and its distribution in time and space for heterotrophic organisms (Yuan et al. 2022). However, only a few researches have demonstrated the relative importance of the HZ compartment in the overall system structure (Collier et al. 2004; Reynolds Jr and Benke 2012a; Wright-Stow and Wilcock 2017). Although initially defined biologically, the uppermost 0 to 5–10 cm of sediments have been labeled as the benthic zone (BZ), while the deeper depths are referred to as the hypoxic zone (Smock et al. 1992); Collier et al. 2004). Accurate delineation of the boundaries of the hyporheic zone compartment's requires a depth-gradient strategy on a microscopic scale, which considers centimetre-scale differences in assemblage structure, and maps the ranges of key species in both habitats.

Multiple studies have demonstrated that as one moves deeper into the water, the composition of invertebrate assemblages undergoes a shift. The control over these communities' changes from large individuals near the surface to a dominance of smaller-bodied species (Schmid-Araya 1994). This alteration in invertebrate communities becomes evident with increasing water depth. The ability of hyporheos taxa's to colonize the HZ varies among species due to several biological factors (Nogaro et al. 2009; Robertson and Wood 2010; Descloux et al. 2014). Sediment agglomeration (Fig. 4) leads to a reduction in oxygen concentration and pore size along the gravity gradient, restricting the dispersal of large macroinvertebrates with high metabolism (Maridet and Philippe 1995; Strayer et al. 2003). Consequently, meiofauna (microscopic metazoans) and protists tend to increase in abundance as one descends into the water (Fig. 4). Studies

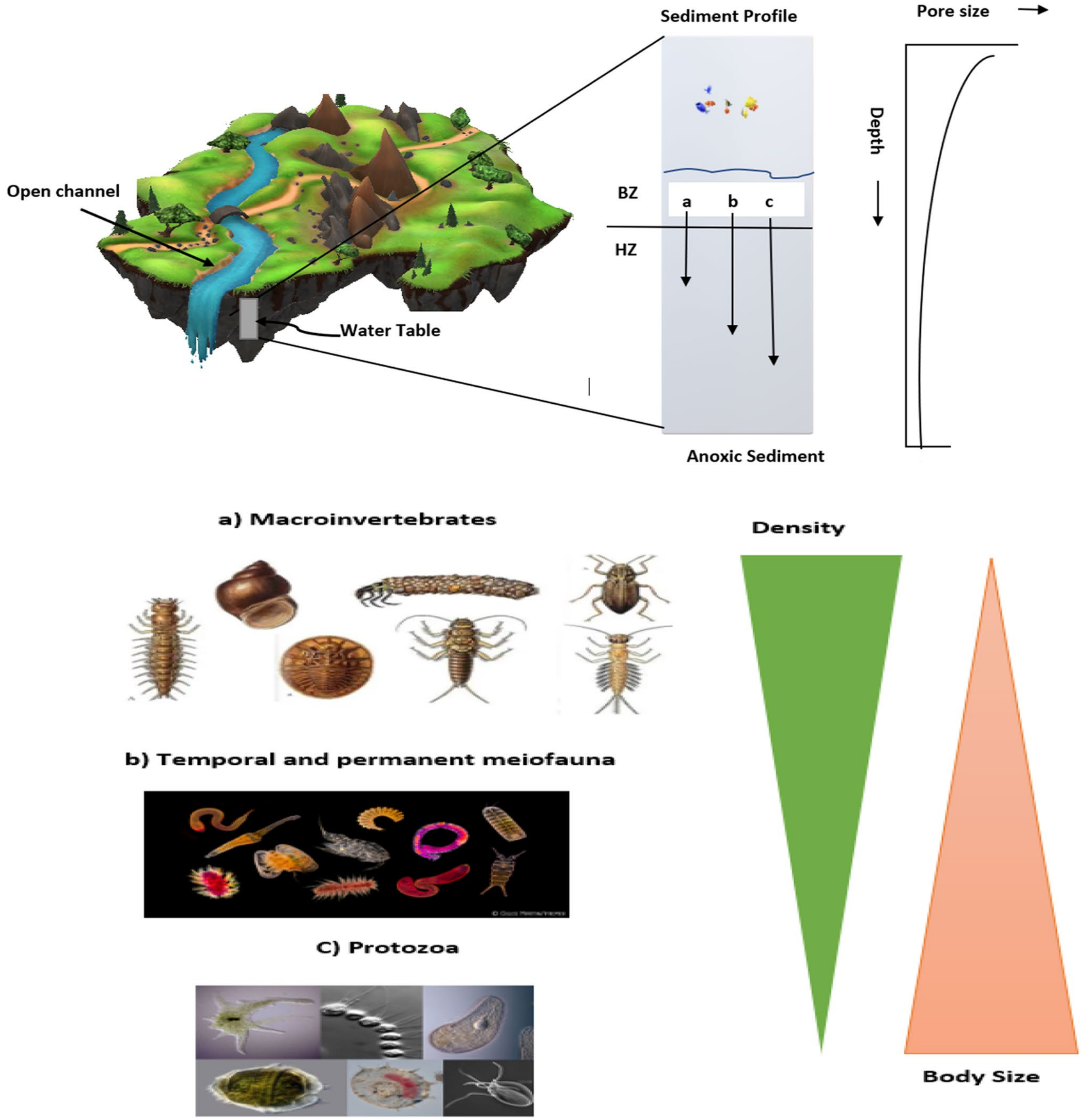

Fig. 4 Box 1: shows a diagram showing the distribution of the streambed community along the depth profile in relation to pore size and redox potential. Large macroinvertebrate colonisation depth is represented by arrows in (**a**), (**b**), and (**c**) respectively. The hypothetical separation between the hyporheic zone (HZ) and benthic zone (BZ), which serves as the cap on colonisation between benthos and hyporheos, is also depicted. The sediment profile's grey/black scale represents the redox potential, with deep black denoting extremely anoxic conditions. Box2: Body size and density distributions of different groups in the community structure. Organisms are not drawn to scale

of riverbank ecosystems have revealed a decline in the density of large species with depth (Marchant et al. 2000; Davy-Bowker et al. 2006; Pacioglu and Robertson 2017). Thus, the loss of riverbed biota and secondary production maybe linked to the gravity gradient as a combination of diverse physicochemical parameters. The meta-analysis of invertebrate communities from diverse river systems, based on information from Smock et al. (1992) and Reynolds Jr and Benke (2012) lends support to this hypothesis by demonstrating a significant and negative effect on secondary production and depth of biomass. It should be noted that the studies included in this meta-analysis have primarily focused on large species, while the majority of meiofauna and protozoa have not been included in the analysis of differences along the depth gradient in terms of secondary production and biomass.

The variability in the ability to infiltrate the HZ is influenced by the characteristics of hyporheic species, and we expect there to be a significant interaction between depth and size. Future studies incorporating these groupings and their interactions with depth, sediment properties, and hydrology, could greatly enhance predictive modeling and compartment comparisons (Wohl 2021). This is particularly intriguing because it has been hypothesized that dynamic hyporheic communities play a crucial role in maintaining the bioreactor function of the HZ (Krause et al. 2014). Thus, areas with higher rates of biomass and secondary production may correspond to hotspots of nutrient and pollutant transformation.

It is also anticipated that the depth gradient would influence the functional behaviour of different organisms within the bioreactor. For instance, relatively large burrowing organisms like Oligochaeta, Ephemeridae nymphs, and Chironomidae larvae, would have a greater impact on the benthic zone and the upper layer of the HZ compared to the deeper layers. Their activities, including bioturbation and bioirrigation, have significant effects on water biogeochemistry by enhancing respiration, permeability, and bacterial activity (Hölker et al. 2015; Baranov et al. 2020).

Hyporheic bioreactor

The health of ecosystems is often negatively affected when human activities alter the chemistry of pore water and flow exchange in the HZ (Peralta-Maraver et al. 2018). The influx of contaminated water from wastewater treatment plants (WWTPs) has led to the continuous or intermittent introduction of nutrients such as organic C, nitrate, phosphate and additional contaminants (such as insecticides) into many rivers worldwide (Rutere et al. 2020; Höhne et al. 2022). Once these molecules enter the sediments due to hydrological patterns, they may undergo metabolic processes facilitated by active and prolific hyporheic communities, resulting in the production of oxidised or reduced substances (Schaper et al. 2018).

Considering the crucial role of microbial biofilm in water purification within the HZ, it can be regarded as a bioreactor. Hyporheic biofilms exhibit highly diverse bacterial and archaeal populations that share a common polysaccharide matrix (Peter et al. 2019). As a result, numerous functional taxonomic units, metabolic capabilities, and sites with high enzymatic activity within these biofilms coexist (Peter et al. 2019). In-stream biofilms exert a significant impact on biogeochemical fluxes of carbon, phosphorus and nitrogen (Rutere et al. 2020). One theory suggests that the physiology, activity, and biomass of microbial communities are constrained by the availability of nutrients (Albergamo et al. 2019). Consequently, increased intake of dissolved organic carbon (DOC) should lead to higher bacterial biomass and metabolic activity (Garcia-Becerra and Ortiz 2018). Water constantly flows into and out of the HZ and riparian zone (Li et al. 2022) due to water level fluctuations that creates significant hydraulic gradients and enhances mixing in regulated waterways. Daily variations in river level increase bacterial respiration and turnover of the organic carbon (Li et al. 2022).

Micropollutants

The HZ refers to the space of the streambed where surface water infiltrates the sediment, leading to a subsurface flow of porewater and potential reemergence into the surface water, a process known as hyporheic exchange flow (Frei et al. 2019).These flows occur at various scales and create hotspots for biogeochemical activity, making the HZ akin to the “liver” of a river (Posselt et al. 2018). The conveyance of O_2, nutrients, and bioavailable organic C to the sub-surface sediment creates an ecohydrological environment with steep redox gradients and increased biological activity (Posselt et al. 2018).

Research (by Lewandowski and Nützmann (2010), Bardini et al. (2012), and Maazouzi et al. (2017) indicates that organic C, phosphorus, and nitrogen, are the major contaminants in the HZ. However, a new class of chemicals called micropollutants poses an emerging threat to both surface water systems and their interactions with groundwater systems. Inputs from wastewater treatment plants (WWTPs) have significantly increased the concentration of micropollutants, including pharmacological and individual care items like ibuprofen or antibiotics, in waterways (Li et al. 2015; Kalekar et al. 2022). These micropollutants raise concern about their potential harmful impacts on environmental systems, such as bioaccumulation, and anthropological toxicity like aquifer contamination. Prolonged exposure to subtherapeutic levels of antibiotics in aquatic systems also acts as a selective mechanism for microbial populations (Hirsch et al. 1999; Yang and Carlson 2003; Schaper et al. 2018). Consequently, the capability of biofilms to provide ecosystem services may be altered due to variations in the bacterial population’s antibiotic resistance (composition, richness, density) (Roose-Amsaleg and Laverman 2016), which can negatively affect denitrifying bacteria subsequently decrease denitrification processes. Nonetheless, in various cases, micropollutants can be effectively reduced along flow pathways (Lewandowski and Nützmann 2010). Biofilms are more efficient at transforming several of these substances, such as diclofenac, bezafibrate, ibuprofen, and naproxen, in stream sediments compared to WWTPs (i.e., Schulz and Sherwood 2008; Radke et al. 2009). This efficacy can be attributed to the diverse microbial communities present in natural environments (Gan et al. 2023). Additionally, biodegradation processes are more efficient in the HZ due to the longer water residence time compared to the open channel (Lewandowski and Nützmann 2010) .

Although the importance of biofilm in pollution mitigation is widely recognized, many unresolved concerns surround the underlying mechanisms of this ecological process, such as the role of the rest of the population (Zhu et al. 2020). When studying the degradation of pollutants and nutrients in the HZ, it is crucial to consider the hierarchical interplay between biogeochemical processes and hydrological patterns (Sophocleous 2002). Hydrodynamics can have two conflicting effects on solute responses in sediments. Higher inward water flows result in shorter residence periods for chemicals in the sediments, giving the hyporheic microbiota less time to undertake biogeochemical reactions (Krause et al. 2017) (Fig. 3a). When the potential influence of hyporheic organisms on hydraulic conductivity is taken into account, these pathways become more complex (Li et al. 2020). The growth of biofilm matrices in sediment pores reduces permeability and enhances water residence time in the HZ (Li et al. 2022). Furthermore, the thickness of the biofilm polysaccharide matrix is believed to be the limiting factor in solute uptake, according to biofilm theory (Gantzer et al. 1988). External mass transfer involves the movement of solutes from the pore water to the biofilm surface, followed by internal mass transfer via the biofilm matrix and into the cells (Battin et al. 2003). However, sediment permeability increases due to the ongoing reworking (Boulton 2000). HZ microfauna, acting as ecosystem engineers, create preferential flow paths, increase the surface area of biofilms, and enhance bacterial densities through burrowing, sediment removal, and biofilm foraging (Boulton 2000; Mermillod-Blondin et al. 2011). Thus, the balance between these competing forces ultimately determines the impact on breakdown rates (Cardenas and Tiedje 2008; Arnon et al. 2010; Bardini et al. 2012). Consequently, carefully planned experiments conducted under defined conditions and employing proper cultivation techniques are necessary to acquire a mechanistic knowledge of biofilm function (Singer et al. 2006).

Future perspectives

Future studies on the attenuation of pollutants in the HZ are expected to focus on the interactions between pollution, hydrology, and community ecology (Kalekar et al. 2022). Understanding how these variables interact is crucial for developing practical strategies to reduce pollution and maintain the health of the HZ (Zhou and Zhou 2023). One area of investigation could be the impact of hydrological variations on pollutant attenuation and transport. For instance, scientists could examine how changes to sediment dynamics, groundwater flow rates, and groundwater level affect the transport and fate of contaminants in the HZ (Dichgans et al. 2023). By understanding these dynamics, researchers could develop predictive models to identify the most vulnerable areas of the HZ to contamination. Another avenue of research could be to explore the role of community ecology in contaminant attenuation (Gan et al. 2023). Microbial communities in the HZ play a significant role in pollutant breakdown and toxicity reduction. Future studies could investigate how changes in the composition and diversity of these microbial communities' influence contaminants attenuation. By gaining a better understanding of the factors that impact microbial communities in the HZ, researchers could develop strategies to promote the growth of microbial communities that are effective at breaking down pollutants (Ren et al. 2023). Furthermore, future research could assess the effectiveness of various remediation strategies in the HZ. For example, researchers could investigate the efficacy of using permeable reactive barriers or other engineered solutions to remove contaminants from groundwater before it enters the HZ (Feng et al. 2023). Additionally, natural processes like bioremediation or phytoremediation could be explored as potential methods to break down contaminants in the HZ.

Conclusion

Still, there are several factors that pose challenges in ecological studies of the HZ. Not only are these factors interconnected in space and time, but they also exhibit a discernible hierarchy. The study of the HZ is emerging as a prominent field in freshwater science, primarily due to the availability of advanced technological methods. While HZ research is still in its early stages, it is poised to become a central focus and challenge for freshwater scientists in the future as they strive to comprehend how the HZ influences the provision and delivery of ecosystem services within the entire river system. Numerous intriguing and unresolved questions remain, such as the impact of hyporheic exchange on energy fluxes within these communities and the fate of pollutants and nutrients as they exit the HZ. The influence of river regulations on hyporheic exchange flow is another area that warrants exploration in future studies. Consequently, the most appropriate approach to address all these challenges is through a comprehensive and interdisciplinary framework at the interface of ecology and hydrology.

Funding information This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Declarations

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Ethical approval This article does not contain any studies involving animals performed by any of the authors.

Consent for publication All authors agree to publish this manuscript.

References

Ahmed F, Srinivasa Rao K (2015) Prioritization of sub-watersheds based on morphometric analysis using remote sensing and geographic information system techniques. Int J Remote Sens GIS 4(2):51–65

Akhtar N, Syakir MI, Ahmad MI, Anees MT, Bin Abu Bakar AF, Mizan SA, Alsaadi SF, Khan MMA, Yusuff MSM (2022) Upscaling of surface water and groundwater interactions in hyporheic zone from local to regional scale. Water 14(4):647

Albergamo V, Schollée JE, Schymanski EL, Helmus R, Timmer H, Hollender J, De Voogt P (2019) Nontarget screening reveals time trends of polar micropollutants in a riverbank filtration system. Environ Sci Technol 53(13):7584–7594

Arnon S, Marx LP, Searcy KE, Packman AI (2010) Effects of overlying velocity, particle size, and biofilm growth on stream–subsurface exchange of particles. Hydrol Process: Int J 24(1):108–114

Arora NK, Mishra I (2022) Sustainable development goal 6: global water security. Environ Sustain 5:271–275. https://doi.org/10.1007/s42398-022-00246-5

Baker RG (2000) Holocene environments reconstructed from plant macrofossils in stream deposits from southeastern Nebraska, USA. Holocene 10(3):357–365

Banks VJ, Palumbo-Roe B, Russell CE (2019) The hyporheic zone. Hydrology-the science of water. IntechOpen, London

Baranov V, Jourdan J, Pilotto F, Wagner R, Haase P (2020) Complex and nonlinear climate-driven changes in freshwater insect communities over 42 years. Conserv Biol 34(5):1241–1251

Bardini L, Boano F, Cardenas MB, Revelli R, Ridolfi L (2012) Nutrient cycling in bedform induced hyporheic zones. Geochim Cosmochim Acta 84:47–61

Battin TJ, Kaplan LA, Newbold D, Hansen CME (2003) Contributions of microbial biofilms to ecosystem processes in stream mesocosms. Nature 426(6965):439–442

Bencala KE, Gooseff MN, Kimball BA (2011) Rethinking hyporheic flow and transient storage to advance understanding of stream-catchment connections. Water Resour Res. https://doi.org/10.1029/2010WR010066

Biehler A, Chaillou G, Buffin-Bélanger T, Baudron P (2020) Hydrological connectivity in the aquifer–river continuum: impact of river stages on the geochemistry of groundwater floodplains. J Hydrol 590:125379

Boano F, Packman AI, Cortis A, Revelli R, Ridolfi L (2007) A continuous time random walk approach to the stream transport of solutes. Water Resour Res 43:W10425. https://doi.org/10.1029/2007WR006062

Boano F, Revelli R, Ridolfi L (2009) Quantifying the impact of groundwater discharge on the surface–subsurface exchange. Hydrol Process: Int J 23(15):2108–2116

Boulton AJ (2000) River ecosystem health down under: assessing ecological condition in riverine groundwater zones in Australia. Ecosyst Health 6(2):108–118

Boulton AJ (2007) Hyporheic rehabilitation in rivers: restoring vertical connectivity. Freshw Biol 52(4):632–650

Boulton AJ, Findlay S, Marmonier P, Stanley EH, Valett HM (1998) The functional significance of the hyporheic zone in streams and rivers. Ann Rev Ecol Syst 29(1):59–81

Boulton AJ, Datry T, Kasahara T, Mutz M, Stanford JA (2010) Ecology and management of the hyporheic zone: stream–groundwater interactions of running waters and their floodplains. J North Am Benthol Soc 29(1):26–40

Bruno MC, Maiolini B, Carolli M, Silveri L (2009) Impact of hydropeaking on hyporheic invertebrates in an Alpine stream (Trentino, Italy). Ann De Limnol Int J Limnol 45(3):157–170

Bruno MC, Doretto A, Boano F, Ridolfi L, Fenoglio S (2020) Role of the hyporheic zone in increasing the resilience of mountain streams facing intermittency. Water 12(7):2034

Buffington JM, Tonina D (2009) Hyporheic exchange in mountain rivers II: Effects of channel morphology on mechanics, scales, and rates of exchange. Geogr Compass 3(3):1038–1062

Cardenas MB (2008) Surface water-groundwater interface geomorphology leads to scaling of residence times. Geophys Res Lett. https://doi.org/10.1029/2008GL033753

Cardenas E, Tiedje JM (2008) New tools for discovering and characterizing microbial diversity. Curr Opin Biotechnol 19(6):544–549

Cardenas MB, Wilson JL, Zlotnik VA (2004) Impact of heterogeneity, bed forms, and stream curvature on subchannel hyporheic exchange. Water Resour Res. https://doi.org/10.1029/2004WR003008

Collier KJ, Wright-Stow AE, Smith BJ (2004) Trophic basis of production for a mayfly in a North Island, New Zealand, forest stream: contributions of benthic versus hyporheic habitats and implications for restoration. N Z J Mar Freshw Res 38(2):301–314

Conant B Jr (2004) Delineating and quantifying ground water discharge zones using streambed temperatures. Groundwater 42(2):243–257

Cooper WT, Chanton JC, D'Andrilli J, Hodgkins SB, Podgorski DC, Stenson AC, Tfaily MM, Wilson RM (2022) A history of molecular level analysis of natural organic matter by FTICR mass spectrometry and the paradigm shift in organic geochemistry. Mass Spectrom Rev 41(2):215–239

Costanzo SD, Murby J, Bates J (2005) Ecosystem response to antibiotics entering the aquatic environment. Mar Pollut Bull 51(1–4):218–223

Davy-Bowker J, Sweeting W, Wright N, Clarke RT, Arnott S (2006) The distribution of benthic and hyporheic macroinvertebrates from the heads and tails of riffles. Hydrobiologia 563(1):109–123

DelVecchia AG, Shanafield M, Zimmer MA, Busch MH, Krabbenhoft CA, Stubbington R, Kaiser KE, Burrows RM, Hosen J, Datry T (2022) Reconceptualizing the hyporheic zone for nonperennial rivers and streams. Freshw Sci 41(2):167–182

Descloux S, Datry T, Usseglio-Polatera P (2014) Trait-based structure of invertebrates along a gradient of sediment colmation: Benthos versus hyporheos responses. Sci Total Environ 466:265–276

Di Lorenzo T, Fiasca B, Di Cicco M, Cifoni M, Galassi DMP (2021) Taxonomic and functional trait variation along a gradient of ammonium contamination in the hyporheic zone of a Mediterranean stream. Ecol Ind 132:108268

Dichgans F, Boos JP, Ahmadi P, Frei S, Fleckenstein JH (2023) Integrated numerical modeling to quantify transport and fate of microplastics in the hyporheic zone. Water Res 243:120349

Dole-Olivier M-J, Des Châtelliers MC, Galassi DMP, Lafont M, Mermillod-Blondin F, Paran F, Graillot D, Gaur S, Marmonier P (2022) Drivers of functional diversity in the hyporheic zone of a large river. Sci Total Environ 843:156985

Dudley-Southern M, Binley A (2015) Temporal responses of groundwater-surface water exchange to successive storm events. Water Resour Res 51(2):1112–1126

Dwivedi D (2019) Geochemical exports to river from the intrameander hyporheic zone under transient hydrologic conditions. Water Resour Res. https://doi.org/10.1029/2018WR023377

Fang Y, Chen X, Gomez Velez J, Zhang X, Duan Z, Hammond GE, Goldman AE, Garayburu-Caruso VA, Graham EB (2020) A multirate mass transfer model to represent the interaction of multicomponent biogeochemical processes between surface water and hyporheic zones (SWAT-MRMT-R 1.0). Geosci Model Dev 13(8):3553–3569

Feng R, Duan L, Shen S, Cheng Y, Wang Y, Wang W, Yang S (2023) Temporal dynamic of antibiotic resistance genes in the Zaohe-Weihe hyporheic zone: driven by oxygen and bacterial community. Ecotoxicology 32(1):57–72

Franken RJ, Storey RG, Dudley Williams D (2001) Biological, chemical and physical characteristics of downwelling and upwelling zones in the hyporheic zone of a north-temperate stream. Hydrobiologia 444:183–195

Frei S, Piehl S, Gilfedder BS, Löder MGJ, Krutzke J, Wilhelm L, Laforsch C (2019) Occurrence of microplastics in the hyporheic zone of rivers. Sci Rep 9(1):15256

Fritz BG, Mackley RD, Arntzen EV, Mendoza DP, Patton GW (2008) Methods for assessing the relative amounts of groundwater discharge into the Columbia river and measurement of Columbia river gradients at the Hanford Site's 300 area. Pacific Northwest National Lab (PNNL). Richland, WA (United States)

Fudyma JD, Chu RK, Grachet G, Stegen N, Tfaily MM (2021) Coupled biotic–abiotic processes control biogeochemical cycling of dissolved organic matter in the Columbia river hyporheic zone. Front Water 2:574692

Gan C, Luo Z, Su C, Tong L, Liu H (2023) Mechanism of reactive co-transport of Fe^{2+} and antibiotics in hyporheic zone simulated by quartz sand column. J Hydrol 621:129641

Gantzer CJ, Rittmann BE, Herricks EE (1988) Mass transport to streambed biofilms. Water Res 22(6):709–722

Garcia-Becerra FY, Ortiz I (2018) Biodegradation of emerging organic micropollutants in nonconventional biological wastewater treatment: a critical review. Environ Eng Sci 35(10):1012–1036

Gasith A, Resh VH (1999) Streams in Mediterranean climate regions: abiotic influences and biotic responses to predictable seasonal events. Annu Rev Ecol Syst 30:51–81

Gomes PIA, Wai OWH (2019) Ecohydrologic structure and function of stream networks with earthen upstream and concrete-lined downstream. Ecohydrology 12(4):e2088

Gomez-Velez JD, Harvey JW (2014) A hydrogeomorphic river network model predicts where and why hyporheic exchange is important in large basins. Geophys Res Lett 41(18):6403–6412

Gomez-Velez JD, Wilson JL, Cardenas MB, Harvey JW (2017) Flow and residence times of dynamic river bank storage and sinuosity-driven hyporheic exchange. Water Resour Res 53(10):8572–8595

Graham ZA, Stubbs MB, Loughman ZJ (2022) Digging ability and digging performance in a hyporheic gravel-dwelling crayfish, the hairy crayfish Cambarus friaufi (Hobbs 1953)(Decapoda Astacidae: Cambaridae). J Crustacean Biol 42(1):ruac002

Guo F, Jiang G (2020) Hydro-ecological processes of hyporheic zone in a karst spring-fed pool: Effects of groundwater decline and river backflow. J Hydrol 587:124987

Hannah DM, Malcolm IA, Bradley C (2009) Seasonal hyporheic temperature dynamics over riffle bedforms. Hydrol Processes: Int J 23(15):2178–2194

Harvey J, Gooseff M (2015) River corridor science: hydrologic exchange and ecological consequences from bedforms to basins. Water Resour Res 51(9):6893–6922

Hirsch R, Ternes T, Haberer K, Kratz K-L (1999) Occurrence of antibiotics in the aquatic environment. Sci Total Environ 225(1–2):109–118

Höhne A, Müller BM, Schulz H, Dara R, Posselt M, Lewandowski J, McCallum JL (2022) Fate of trace organic compounds in the hyporheic zone: influence of microbial metabolism. Water Res 224:119056

Hölker F, Wurzbacher C, Weißenborn C, Monaghan MT, Holzhauer SIJ, Premke K (2015) Microbial diversity and community respiration in freshwater sediments influenced by artificial light at night. Philos Trans Royal Soc B: Biol Sci 370(1667):20140130

Huang S, Yang JQ (2022) Impacts of emergent vegetation on hyporheic exchange. Geophys Res Lett 49(13):e2022GL099095

Hübner D, Gerke M, Fricke R, Schneider J, Winkelmann C (2020) Cypriniform fish in running waters reduce hyporheic oxygen depletion in a eutrophic river. Freshw Biol 65(9):1518–1528

Iepure S, Gomez-Ortiz D, Lillo J, Rasines-Ladero R, Di Lorenzo T (2022) Applying electrical resistivity tomography and biological methods to assess the hyporheic zone water exchanges in two Mediterranean stream reaches. Water 14(21):3396

Kaiser KE (2022) Reconceptualizing the hyporheic zone for nonperennial rivers and streams. Freshw Sci

Kalekar P, Kamble P, Chakraborti S et al (2022) Heavy metal contamination in surface sediments of the Upper Bhima Basin, Maharashtra, India. Environ Sustain 5:507–531

Kasahara T, Li Y, Tanaka A (2022) Effects of dams and reservoirs on organic matter decomposition in the hyporheic zone in forest mountain streams. Hydrobiologia 849(13):2949–2965

Krause S, Heathwaite L, Binley A, Keenan P (2009) Nitrate concentration changes at the groundwater-surface water interface of a small Cumbrian river. Hydrol Processes: Int J 23(15):2195–2211

Krause S, Lewandowski J, Grimm NB, Hannah DM, Pinay G, McDonald K, Martí E, Argerich A, Pfister L, Klaus J (2017) Ecohydrological interfaces as hot spots of ecosystem processes. Water Resour Res 53(8):6359–6376

Krause S, Abbott BW, Baranov V, Bernal S, Blaen P, Datry T, Drummond J, Fleckenstein JH, Velez JG, Hannah DM, Knapp JL (2022) Organizational principles of hyporheic exchange flow and biogeochemical cycling in river networks across scales. Water Res Res 58(3):e2021WR029771

Langenhoff A, Inderfurth N, Veuskens T, Schraa G, Blokland M, Kujawa-Roeleveld K, Rijnaarts H (2013) Microbial removal of the pharmaceutical compounds ibuprofen and diclofenac from wastewater. BioMed Res Int 2013:325806. https://doi.org/10.1155/2013/325806

Lapham L, Buser-Young J, Thurber A, Colwell F (2021) River and hyporheic zone water geochemical data from OsmoSamplers, East River Pumphouse, Colorado, Nov 2017-Sept 2018. Environmental system science data infrastructure for a virtual ecosystem (ESS-DIVE) (United States); Quantifying subsurface biogeochemical variability in a high altitude watershed during winter isolation

Lewandowski J, Nützmann G (2010) Nutrient retention and release in a floodplain's aquifer and in the hyporheic zone of a lowland river. Ecol Eng 36(9):1156–1166

Li Z, Sobek A, Radke M (2015) Flume experiments to investigate the environmental fate of pharmaceuticals and their transformation products in streams. Environ Sci Technol 49(10):6009–6017

Li S-L, Xu S, Wang T-J, Yue F-J, Peng T, Zhong J, Wang L-C, Chen J-A, Wang S-J, Chen X (2020) Effects of agricultural activities coupled with karst structures on riverine biogeochemical cycles and environmental quality in the karst region. Agric Ecosyst Environ 303:107120

Li S, Li B, Liu H, Qi W, Yang Y, Yu G, Qu J (2022) The biogeochemical responses of hyporheic groundwater to the long-run managed aquifer recharge: Linking microbial communities to hydrochemistry and micropollutants. J Hazard Mater 431:128587
Liang D, Song J, Xia J, Chang J, Kong F, Sun H, Cheng D, Zhang Y (2022) Effects of heavy metals and hyporheic exchange on microbial community structure and functions in hyporheic zone. J Environ Manage 303:114201
Luo Y, Zhang Z, Chhowalla M, Liu B (2022) Recent advances in design of electrocatalysts for high-current-density water splitting. Adv Mater 34(16):2108133
Maazouzi C, Galassi D, Claret C, Cellot B, Fiers F, Martin D, Marmonier P, Dole-Olivier M (2017) Do benthic invertebrates use hyporheic refuges during streambed drying? A manipulative field experiment in nested hyporheic flowpaths. Ecohydrology 10(6):e1865
Maier HS, Howard KWF (2011) Influence of oscillating flow on hyporheic zone development. Groundwater 49(6):830–844
Malzone JM, Anseeuw SK, Lowry CS, Allen-King R (2016) Temporal hyporheic zone response to water table fluctuations. Groundwater 54(2):274–285
Marchant R, Wells F, Newall P (2000) Assessment of an ecoregion approach for classifying macroinvertebrate assemblages from streams in Victoria, Australia. J North Am Benthol Soc 19(3):497–500
Marciniak M, Ziułkiewicz M, Górecki M (2022) Variability of water exchange in the hyporheic zone of a lowland river in Poland based on gradientometric studies. Quaest Geogr. https://doi.org/10.2478/quageo-2022-0030
Maridet L, Philippe M (1995) Influence of substrate characteristics on the vertical distribution of stream macroinvertebrates in the hyporheic zone. Folia Fac Sci Nat Univ Masarykianae Brunensis 91:101–105
McCallum JL, Shanafield M (2016) Residence times of stream-groundwater exchanges due to transient stream stage fluctuations. Water Resour Res 52(3):2059–2073
Mendoza-Lera C, Ribot M, Foulquier A, Martí E, Bonnineau C, Breil P, Datry T (2019) Exploring the role of hydraulic conductivity on the contribution of the hyporheic zone to in-stream nitrogen uptake. Ecohydrology 12(7):e2139
Mermillod-Blondin F (2011) The functional significance of bioturbation and biodeposition on biogeochemical processes at the water–sediment interface in freshwater and marine ecosystems. J North Amer Benthol Soc 30(3):770–778
Mermillod-Blondin F, Foulquier A, Maazouzi C, Navel S, Negrutiu Y, Vienney A, Simon L, Marmonier P (2013) Ecological assessment of groundwater trophic status by using artificial substrates to monitor biofilm growth and activity. Ecol Ind 25:230–238
Michaelis T, Wunderlich A, Coskun ÖK, Orsi W, Baumann T, Einsiedl F (2022) High-resolution vertical biogeochemical profiles in the hyporheic zone reveal insights into microbial methane cycling. Biogeosciences 19(18):4551–4569
Milner VS, Jones JI, Maddock IP, Bunting GC (2022) The hyporheic zone as an invertebrate refuge during a fine sediment disturbance event. Ecohydrology 15(6):e2450
Nelson AR, Sawyer AH, Gabor RS, Saup CM, Bryant SR, Harris KD, Briggs MA, Williams KH, Wilkins MJ (2019) Heterogeneity in hyporheic flow, pore water chemistry, and microbial community composition in an alpine streambed. J Geophys Rese: Biogeosci 124(11):3465–3478
Nogaro G, Mermillod-Blondin F, Valett MH, François-Carcaillet F, Gaudet J-P, Lafont M, Gibert J (2009) Ecosystem engineering at the sediment–water interface: bioturbation and consumer-substrate interaction. Oecologia 161(1):125–138
Olsen DA, Townsend CR (2003) Hyporheic community composition in a gravel-bed stream: influence of vertical hydrological exchange, sediment structure and physicochemistry. Freshw Biol 48(8):1363–1378
Pacioglu O, Robertson A (2017) The invertebrate community of the chalk stream hyporheic zone: spatio-temporal distribution patterns. Knowl Manage Aquat Ecosyst 418:10
Packman AI, Salehin M, Zaramella M (2004) Hyporheic exchange with gravel beds: Basic hydrodynamic interactions and bedform-induced advective flows. J Hydraul Eng 130(7):647–656
Peralta-Maraver I, Reiss J, Robertson AL (2018) Interplay of hydrology, community ecology and pollutant attenuation in the hyporheic zone. Sci Total Environ 610:267–275
Peter KT, Herzog S, Tian Z, Wu C, McCray JE, Lynch K, Kolodziej EP (2019) Evaluating emerging organic contaminant removal in an engineered hyporheic zone using high resolution mass spectrometry. Water Res 150:140–152
Poole GC, O'daniel SJ, Jones KL, Woessner WW, Bernhardt ES, Helton AM, Stanford JA, Boer BR, Beechie TJ (2008) Hydrologic spiralling: the role of multiple interactive flow paths in stream ecosystems. River Res Appl 24(7):1018–1031
Poole GC, Fogg SK, O'Daniel SJ, Amerson BE, Reinhold AM, Carlson SP, Mohr EJ, Oakland HC (2022) Hyporheic hydraulic geometry: conceptualizing relationships among hyporheic exchange, storage, and water age. PLoS ONE 17(1):e0262080
Posselt M, Jaeger A, Schaper JL, Radke M, Benskin JP (2018) Determination of polar organic micropollutants in surface and pore water by high-resolution sampling-direct injection-ultra high performance liquid chromatography-tandem mass spectrometry. Environ Sci: Process Impacts 20(12):1716–1727
Radke M, Lauwigi C, Heinkele G, Mürdter TE, Letzel M (2009) Fate of the antibiotic sulfamethoxazole and its two major human metabolites in a water sediment test. Environ Sci Technol 43(9):3135–3141
Reidy CA, Clinton SM (2004) Down under: hyporheic zones and their function. University of Washington Water Center
Ren J, Hu H, Lu X, Yu R (2023) Water and heat exchange responses to flooding and local storm events in the hyporheic zone driven by a meandering bend. Sci Total Environ 883:163732
Reynolds SK Jr, Benke AC (2012) Chironomid production along a hyporheic gradient in contrasting stream types. Freshw Sci 31(1):167–181
Robertson AL, Wood PJ (2010) Ecology of the hyporheic zone: origins, current knowledge and future directions. Fundam Appl Limnol 176(4):279–289
Roose-Amsaleg C, Laverman AM (2016) Do antibiotics have environmental side-effects? Impact of synthetic antibiotics on biogeochemical processes. Environ Sci Pollut Res 23(5):4000–4012
Runkel RL (2007) Toward a transport-based analysis of nutrient spiraling and uptake in streams. Limnol Oceanogr: Methods 5(1):50–62
Rutere C, Posselt M, Horn MA (2020) Fate of trace organic compounds in hyporheic zone sediments of contrasting organic carbon content and impact on the microbiome. Water 12(12):3518
Sackett JD, Shope CL, Bruckner JC, Wallace J, Cooper CA, Moser DP (2019) Microbial community structure and metabolic potential of the hyporheic zone of a large mid-stream channel bar. Geomicrobiol J 36(9):765–776
Schaper JL, Seher W, Nützmann G, Putschew A, Jekel M, Lewandowski J (2018) The fate of polar trace organic compounds in the hyporheic zone. Water Res 140:158–166
Schmadel NM, Ward AS, Kurz MJ, Fleckenstein JH, Zarnetske JP, Hannah DM, Blume T, Vieweg M, Blaen PJ, Schmidt C (2016) Stream solute tracer timescales changing with discharge and reach length confound process interpretation. Water Resour Res 52(4):3227–3245

Schmid-Araya JM (1994) Spatial and temporal distribution of micro-meiofaunal groups in an alpine gravel stream. Int Ver Theor Angew Limnol: Verh 25(3):1649–1655

Schulz R, Sherwood PR (2008) Physical and mental health effects of family caregiving. J Soc Work Educ 44:105–113

Singer G, Besemer K, Hödl I, Chlup A, Hochedlinger G, Stadler P, Battin TJ (2006) Microcosm design and evaluation to study stream microbial biofilms. Limnol Oceanogr: Methods 4(11):436–447

Singer MB, Stella JC, Dufour S, Piégay H, Wilson RJ, Johnstone L (2013) Contrasting water-uptake and growth responses to drought in co-occurring riparian tree species. Ecohydrology 6(3):402–412

Singh T, Gomez-Velez JD, Wu L, Wörman A, Hannah DM, Krause S (2020) Effects of successive peak flow events on hyporheic exchange and residence times. Water Resour Res 56(8):e2020WR027113

Smock LA, Gladden JE, Riekenberg JL, Smith LC, Black CR (1992) Lotic macroinvertebrate production in three dimensions: channel surface, hyporheic, and floodplain environments. Ecology 73(3):876–886

Sobczak WV, Findlay S (2002) Variation in bioavailability of dissolved organic carbon among stream hyporheic flowpaths. Ecology 83(11):3194–3209

Son K, Fang Y, GomezVelez JD, Byun K, Chen X (2022) Combined effects of stream hydrology and land use on basin-scale hyporheic zone denitrification in the Columbia River Basin. Water Resour Res. https://doi.org/10.1029/2021WR031131

Sophocleous M (2002) Interactions between groundwater and surface water: the state of the science. Hydrogeol J 10(1):52–67

Stanley EH, Boulton AJ (1993) Hydrology and the distribution of hyporheos: perspectives from a mesic river and a desert stream. J North Amer Benthol Soc 12(1):79–83

Storey RG, Howard KWF, Williams DD (2003) Factors controlling riffle-scale hyporheic exchange flows and their seasonal changes in a gaining stream: a three-dimensional groundwater flow model. Water Resour Res 39(2):1034. https://doi.org/10.1029/2002WR001367

Strayer DL, Beighley RE, Thompson LC, Brooks S, Nilsson C, Pinay G, Naiman RJ (2003) Effects of land cover on stream ecosystems: roles of empirical models and scaling issues. Ecosystems 6(5):407–423

Stubbington R (2012) The hyporheic zone as an invertebrate refuge: a review of variability in space, time, taxa and behaviour. Mar Freshw Res 63(4):293–311

Tewari A, Singh PK, Gaur S (2022) Engineered hyporheic zones: design and applications in stream health restoration–a review. Water Supply 22(2):2179–2193

Torgeson JM, Rosenfeld CE, Dunshee AJ, Duhn K, Schmitter R, O'Hara PA, Ng GHC, Santelli CM (2022) Hydrobiogechemical interactions in the hyporheic zone of a sulfate-impacted, freshwater stream and riparian wetland ecosystem. Environ Sci: Process Impacts 24(9):1360–1382

Trauth N, Fleckenstein JH (2017) Single discharge events increase reactive efficiency of the hyporheic zone. Water Resour Res 53(1):779–798

van Grinsven HJM, Bouwman L, Cassman KG, van Es HM, McCrackin ML, Beusen AHW (2015) Losses of ammonia and nitrate from agriculture and their effect on nitrogen recovery in the European Union and the United States between 1900 and 2050. J Environ Qual 44(2):356–367

Vaux WG (1968) Intragravel flow and interchange of water in a streambed. Fish Bull Fish Wildl Service 66(3):479–489

Vonk JE, Tank SE, Walvoord MA (2019) Integrating hydrology and biogeochemistry across frozen landscapes. Nat Commun 10(1):5377

Ward AS (2016) The evolution and state of interdisciplinary hyporheic research. Wiley Interdiscip Rev: Water 3(1):83–103

Ward AS, Schmadel NM, Wondzell SM (2018) Simulation of dynamic expansion, contraction, and connectivity in a mountain stream network. Adv Water Resour 114:64–82

Wohl E (2021) An integrative conceptualization of floodplain storage. Rev Geophys 59(2):e2020RG000724

Wright-Stow AE, Wilcock RJ (2017) Responses of stream macroinvertebrate communities and water quality of five dairy farming streams following adoption of mitigation practices. N Z J Mar Freshwat Res 51(1):127–145

Yan A, Guo X, Hu D, Chen X (2022) Reactive transport of NH_4^+ in the hyporheic zone from the ground water to the surface water. Water 14(8):1237

Yang S, Carlson K (2003) Evolution of antibiotic occurrence in a river through pristine, urban and agricultural landscapes. Water Res 37(19):4645–4656

Yang Y, Liu W, Zhang Z, Grossart H-P, Gadd GM (2020) Microplastics provide new microbial niches in aquatic environments. Appl Microbiol Biotechnol 104(15):6501–6511

Yu K, Duan Y, Liao P, Xie L, Li Q, Ning Z, Liu C (2020) Watershed-scale distributions of heavy metals in the hyporheic zones of a heavily polluted Maozhou River watershed, southern China. Chemosphere 239:124773

Yuan X, Liu T, Fox P, Bhattacharyya A, Dwivedi D, Williams KH, Davis JA, Waite TD, Nico PS (2022) Production of hydrogen peroxide in an intra-meander hyporheic zone at East River, Colorado. Sci Rep 12(1):1–10

Zhou T, Endreny TA (2013) Reshaping of the hyporheic zone beneath river restoration structures: Flume and hydrodynamic experiments. Water Resour Res 49(8):5009–5020

Zhou Z, Zhou Z (2023) Investigating the hydrodynamic and biogeochemical evolutions of the hyporheic zone due to large-scale reservoir impoundment. J Hydrol 620:129475

Zhu A, Yang Z, Liang Z, Gao L, Li R, Hou L, Li S, Xie Z, Wu Y, Chen J, 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. J Hydrol 583:124622