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Engineered hyporheic zones: design and applications in stream health restoration – a review

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ABSTRACT

Anthropogenic deterioration of streams and rivers has affected their surface-subsurface linkages. This has led to the degradation of hyporheic zones, a sensitive interface between a stream channel and its surrounding sediments, responsible for transforming pollutants, natural solutes and supporting benthic communities. Several authors have reported the influence of stream restoration measures on hyporheic exchanges and have called for the inclusion of hyporheic zone restorations in stream management. Engineered Hyporheic Zones (EHZ) are the creation of artificial transition areas due to induced hyporheic flows, brought about by some feature modifications done to the stream channel or its subsurface. These feature modifications and their implications have been investigated through lab experiments, outdoor flumes, modelling and field studies for several years. This paper attempts to summarize the endeavours made in the study of EHZ and its applications in water quality improvement and habitat restoration. A comprehensive review of up-to-date literature with specific focus on the influence of engineered structures on hyporheic exchanges is presented, followed by the comparison of preferences opted for different studies and their limitations. The paper ends with suggestive future scope in EHZ studies and its potential as a low cost alternative treatment technology for river restoration.

Key words: engineered hyporheic zone, hyporheic exchange flows, hyporheic zone, stream health restoration, urban stream management

HIGHLIGHTS

- Active management of Hyporheic Zones can improve river health.
- Surface and subsurface feature modifications influence hyporheic flux.
- Hyporheic Zones can be engineered for target pollutant removal.
- Engineered HZ can be a viable, low-cost, alternative treatment technology in developing countries.

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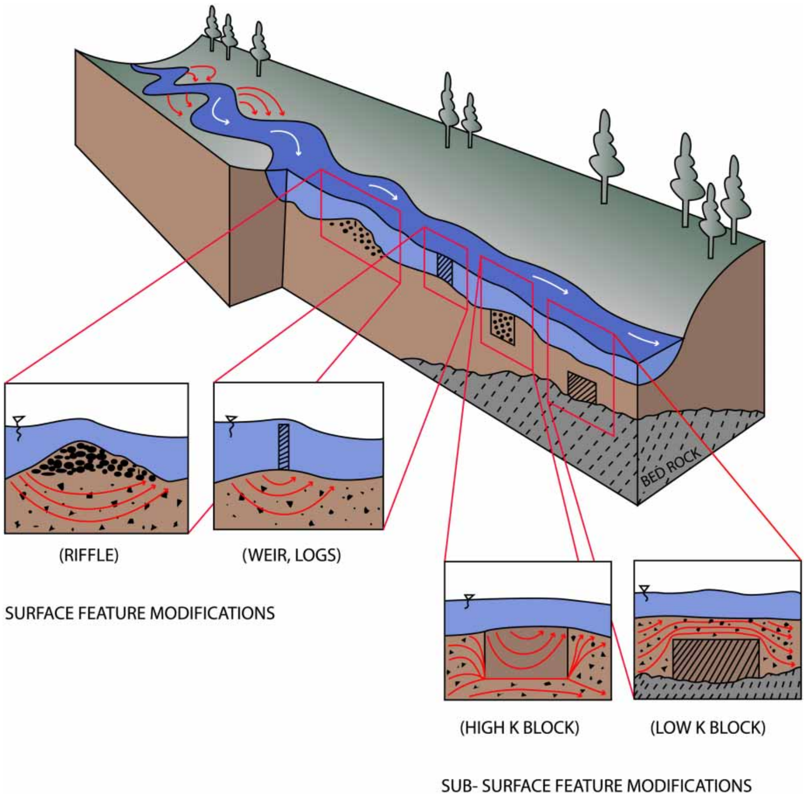
GRAPHICAL ABSTRACT



INTRODUCTION

Intense anthropogenic activities due to rapid growth in population and urbanization have destroyed the natural self-purification capacity of urban rivers (Baca *et al.* 2005; Komínková 2012). Such unplanned increase in urban population have not only caused high demand for potable water but also severely polluted the available water resources (Karn & Harada 2001) and as the rate of land use and climate change escalates, the competition for ecological services of rivers further intensifies (Boano *et al.* 2014). These effects are much more prominent in developing countries, where the average rate of urbanization is much higher (Karn & Harada 2001), topped with unplanned growth and amplified population densities due to human migration (McMichael 2000; Capps *et al.* 2016). About 90% of sewage was directly discharged into rivers in developing countries (UN-Water 2008) and due to its economic, political and social conditions, it would take at least 20 years to build all necessary infrastructure to control river pollution (Baca *et al.* 2005) and yet, even today, it seems a distant reality. Thus, keeping in view the economic reality of developing countries, there is an urgent requirement for alternative low cost treatment technologies to address this growing problem of urban river degradation.

The Hyporheic Zone (HZ) has been at the heart of discussion while talking about stream restorations for several years now (Boulton 2007; Hester & Doyle 2008; Robertson & Merkley 2009; Boulton *et al.* 2010; Hester & Gooseff 2010; Ward *et al.* 2011; Lawrence *et al.* 2013; Herzog *et al.* 2016, 2018). It can be attributed to the established contributions offered by the zone to an assortment of ecosystem services and downstream water quality (Findlay 1995; Brunke & Gonser 1997; Krause *et al.* 2011). Orghidan (1959) was the first to recognise this transition area between ground and surface water as a distinct zone of invertebrate assemblage and called it the 'Hyporheische Biotop', which meant 'under + flow' biotope (Boulton *et al.* 2010). The distinct invertebrates found there came to be widely known as 'hyporheos' (Brunke & Gonser 1997) and the space as the hyporheic zone. Boulton *et al.* (2010) discussed the initial attempts to delineate HZ was based on distribution of surface and subsurface invertebrates, followed by delineation based on temperature as tracer (White & Sully 1987) and solute as tracer (Triska *et al.* 1989). Harvey *et al.* (1996) defined hyporheic exchange as movement of water between channel and subsurface at small scales of centimetre to meter. Triska *et al.* (1989) suggested that at least 10% constituent of surface water, with a

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maximum of 98%, defined the hydrological boundary of the zone and this holds true even for modern day modelling studies (Lautz & Siegel 2006). Boano *et al.* (2014) quoted that Vaux (1968) may have been the first to develop a physically based model to study hyporheic flows. The authors account that individual works of Bencala & Walters (1983) and Thibodeaux & Boyle (1987) shed new information on bidirectional exchange flows and its subsequent modelling by Harvey & Bencala (1993) and Elliott & Brooks (1997a, 1997b) laid the groundwork for appreciating hyporheic flows and their interactions with stream and sediments.

Although HZ studies have been ongoing for over seven decades (Lewandowski *et al.* 2019), there is still no clear single definition available to cover all aspects of this zone. The multi-disciplinary nature and the spatiotemporal dynamism of the zone (Gooseff 2010; Ward 2016) make it difficult to give it a static definition (Brunke & Gonser 1997) and a discipline-specific definition would not convey the same concise meaning across disciplines (White 1993). In addition, the definitions varied not only among different disciplines but also within the same discipline (Gooseff 2010; Ward 2016; Lewandowski *et al.* 2019). Gooseff (2010) and Ward (2016) did a comprehensive discussion and comparison of HZ definitions from different disciplines. Gooseff (2010) purposed a concept of residence time to define HZ, for example, a '24-hour HZ' meant that it took 24 hours for a parcel of water to travel from surface to subsurface, mix and return back. Ward (2016) defined it as a location in streambeds and banks meeting certain criteria. Gooseff (2010) definition would promote unification among interdisciplinary studies by allowing an organized approach, linking different scales of studies and timescales of exchange to timescales of processes. Ward (2016) and Lewandowski *et al.* (2019) defined HZ as any location in the subsurface saturated with flows originating and ending in the surface, whose residence time was in scale of relevance to the processes and the phenomenon occurred repeatedly. Lewandowski *et al.* (2019) believed that such criteria would not only be flexible and encompass all the existing definitions, but also enable other researchers to define HZ at different scales.

The anthropogenic deterioration of streams and rivers has resulted in degradation of the HZ (Boulton 2007; Lawrence *et al.* 2013). Hancock (2002) reviewed the effect of human activities on ecosystem functions of the HZ and listed its potential direct or indirect involvement on HZ processes impairment. Active HZ management could provide an excellent and rather unexplored opportunity to improve water quality and support the biodiversity of urban rivers (Lawrence *et al.* 2013). Bischel *et al.* (2013) states that in order to restore the ecology and aesthetics of urban streams, municipal wastewater effluents and urban runoff need to be envisioned as resources. Engineering of such zones has been paralleled to constructed wetlands on the basis of enhancements provided to the water quality and habitat (Lawrence *et al.* 2013); additionally it negates requirements like space, skilled personnel and infrastructure (Peter *et al.* 2019), which would have been a major limitation in any low-income developing country. Moreover, low-income countries have a wide range of climatic conditions, creating a broad range of scenarios (Capps *et al.* 2016), some of which may be favourable for hyporheic reactions, as the microbial activity and dissolved oxygen in water is controlled by water temperatures (Zarnetske *et al.* 2011) which subsequently depend upon the ambient air temperature (Lawrence *et al.* 2013). Hence, engineered HZ explorations could be the answer to the growing problem of urban river pollution in developing countries, which until now has been limited to developed countries.

Stream restoration measures adopted to protect streams from further deterioration have also had an influence on the hyporheic exchanges underneath the structures (Kasahara & Wondzell 2003). Several key review papers have been published on HZ processes, functions and significance (refer Lewandowski *et al.* 2019) but as per our knowledge, no review has been done on the induced hyporheic exchanges due to engineered systems. This paper attempts to assimilate literature pertaining to applications of engineered HZ formations in inducing Hyporheic Exchange Flows (HEF) in stream channels, to bring about water quality and ecological changes. The main objective of this paper is (1) to summarize the developments in Engineered Hyporheic Zone (EHZ) studies over the years; (2) to investigate the effectiveness of different structures and setups adopted in inducing HEF; (3) to identify the limitations and research gaps; and (4) to suggest future scope of EHZ applications. The literature examined are in the form of EHZ divided into sub headings surface and subsurface feature modifications followed by its discussion, limitations, future scope and conclusion.

ENGINEERED HYPORHEIC ZONE

Several authors have previously suggested inclusion of engineered elements into stream restoration projects (Hancock 2002; Boulton *et al.* 2010; Lawrence *et al.* 2013) and it is gradually gaining importance in the research field with a sharp rise in the number of papers published in the last fifteen years. (Cardenas 2015; Ward 2016). Although feature modification for hyporheic profits was being researched under different names like engineered elements, engineered flows, and hyporheic

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engineering (Gooseff 2010; Lawrence *et al.* 2013), the exact term 'Engineered Hyporheic Zone' (EHZ) was only recently mentioned (Herzog *et al.* 2018; Lewandowski *et al.* 2019; Peter *et al.* 2019). For the purpose of this review, this paper defines an Engineered Hyporheic Zone (EHZ) as any space where hyporheic processes occur due to modification of the HZ itself or the channel (surface or subsurface) or floodplains, intentionally or unintentionally, similar to the definition of hyporheic processes given by Ward (2016).

Bedform features like dunes, riffle-pools and gravel bars, in-stream geomorphic structures like cross vanes, dams, log jams and meanders and sudden change in streambed permeability due to buried structures (Figure 1) all influence hyporheic exchanges in stream channels (Kasahara & Hill 2006, 2007; Lautz & Siegel 2006; Hester & Doyle 2008; Ward *et al.* 2011). Broadly, these exchanges can be categorized as lateral or longitudinal, depending upon the direction of HEF induced by the structure (Kasahara & Hill 2007), while the structures can be labeled as surface or subsurface feature modifications based on their placement on the streambed (Ward *et al.* 2011). In this paper, the literature is reviewed under the surface and subsurface feature modification. Although numerous literature is available on induced hyporheic exchanges due to engineered elements, this review is focused on specific papers where the main objective of the engineered elements was enhanced hyporheic exchanges and pollutant removal.

Surface feature modification

In-stream geomorphic features like riffle-steps, gravel bars, meanders, debris/log dams and partially spanning structures like rock vanes or J-hooks, which are commonly used in channel protection and restoration (Kasahara & Hill 2006; Hester &

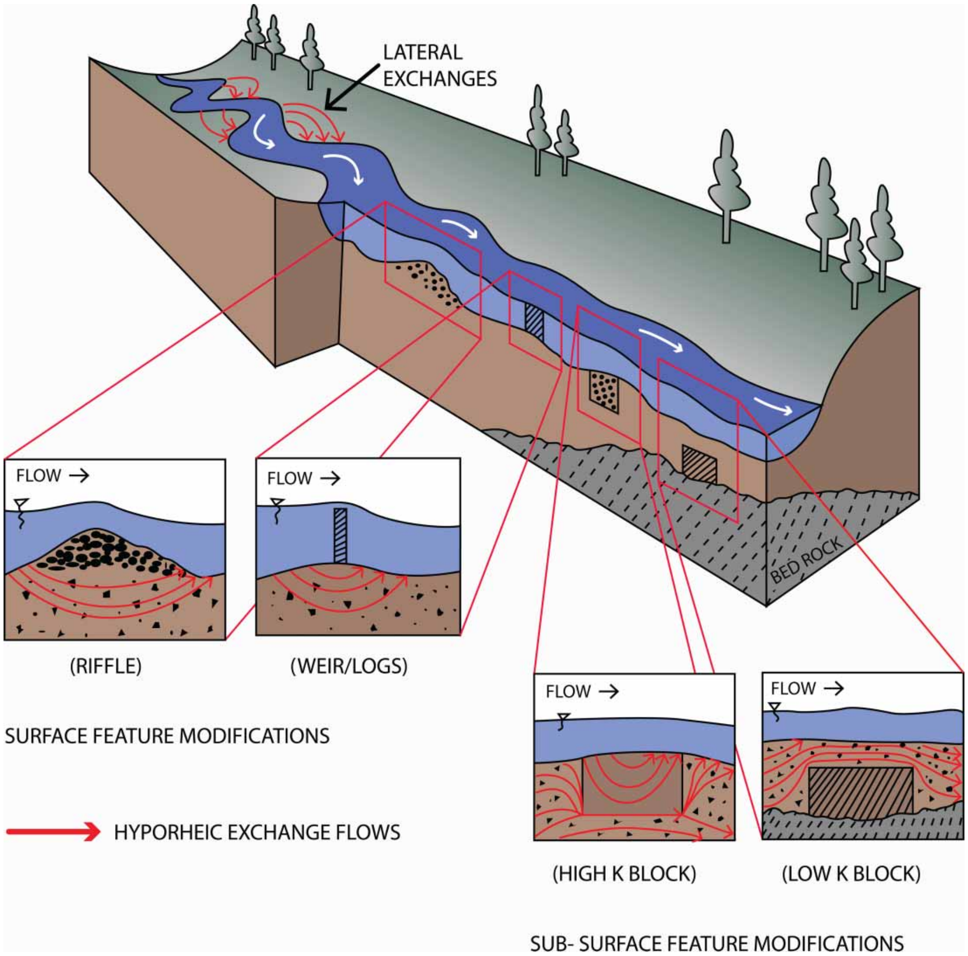

Figure 1 | Diagrammatic illustration of induced Hyporheic Exchange Flows (HEF) due to surface (riffles, weirs/logs) and subsurface {high and low hydraulic conductivity (K) blocks} feature modifications, modified from (Kasahara & Hill 2006; Boulton 2007; Ward *et al.* 2011; Cardenas 2015).

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Doyle 2008; Hester *et al.* 2018) are all categorized under surface feature modifications (Ward *et al.* 2011). These restoration features have been considered as the primary physical drivers of hyporheic exchanges (Brunke & Gonser 1997; Elliott & Brooks 1997a) and numerous studies have documented their influences on HEF and its ecological aspects (Harvey & Bencala 1993; Kasahara & Wondzell 2003; Storey *et al.* 2003; Gooseff *et al.* 2006; Tonina & Buffington 2007). Crispell & Endreny (2009) reported that Kasahara & Hill (2006) was the first to explore the effect of in-channel restoration on hyporheic exchanges. Surface feature modifications can be considered as an indirect method of inducing HEF, as they are usually not induced directly due to the structures, but often by the secondary bedforms created by them (Gordon *et al.* 2013).

Tracers have been commonly used in field studies of hyporheic exchanges (HE). Kasahara & Hill (2006, 2007) studied the effect of longitudinal-constructed riffle, step, and lateral- gravel bar and re-meandered stream restoration measures on HEF and hyporheic zone chemistry, in a lowland stream near Toronto, Ontario, Canada. Using conservative and non-conservative tracers, nitrate removal rate of over 90% was observed in the restored reaches, but it was not even one percent of the daily stream load. Longitudinal HEF were larger than lateral HEF for the same length of stretch and problem of progressive clogging reduced its performance. The authors suggested that while such streambed elements were successful in inducing hyporheic flux and biogeochemical reactions, it would require large stretches of engineered interventions to bring about noticeable changes in surface water chemistry. Zarnetske *et al.* (2011) conducted similar stream tracer studies on a third-order stream in western Oregon, USA, to investigate the HZ induced denitrification dynamics in gravel bars. Aerobic metabolic processes dominated short residence times, while longer timescales were required for denitrification to occur. The daily and seasonal changes in hydraulic, temperature, and chemical composition of water influenced the residence time threshold between processes. The authors state that sampling procedures might affect results due to mixing of oxic water while drawing samples. Gordon *et al.* (2013) used thermal tracers and chemical data to characterize the effect of cross-vane restoration structures on HEF and biogeochemistry of three lowland degraded streams in and around central New York, USA. They reported that low magnitude flux and biogeochemical cycling developed around the structures, which did not contribute to whole-stream system chemistry. The authors reported that secondary pools and riffles created due to cross-vane structures was more effective in inducing HEF and emphasized the importance of generating such secondary bedforms for more efficient exchanges. Doughty *et al.* (2020) explored the effect of channel spanning logjams on HEF in Little Beaver Creek, a third order tributary of Cache la Poudre River, northern Colorado, USA. The study was first to present the use of electrical resistivity in characterizing the increased HEF and complex pathways in the system. The extent and magnitude of HEF increased with the increase in discharge rates. Lack of field data and a suitable control channel limited appropriate interpretation of results.

Flume studies have been useful in explorations of feature-based influences on hyporheic exchanges (HE). Studies conducted by Mutz *et al.* (2007), Tonina & Buffington (2007), Zhou & Endreny (2013) and Dudunake *et al.* (2020) have investigated the effect of engineered elements like a log jam, gravel pool-riffle, boulders and cobble vanes bedform sequence on induced HEF. While Mutz *et al.* (2007) reported that introduction of wood tripled flow resistance and increased the vertical water flux, mixing depth and sediment pore water volume, Tonina & Buffington (2007) observed that the exchanges induced by bedforms was controlled by discharge and topographic submergence of the structures. Mutz *et al.* (2007) stated that the study was nontransferable to real streams, whereas 2D modelling gave poor performance in a gravel bed setting for Tonina & Buffington (2007). Zhou & Endreny (2013) investigated the impact of pool riffle bedform with and without channel spanning cobbles and observed that cobble structures created relatively higher vertical flux, but with reduced mixing depths. The authors attributed that the low bed pressure created downstream of the structure counter-balanced the downwelling forces, thus reducing the penetration depth. Dudunake *et al.* (2020) tried to comprehend the effect of morphological changes induced by boulders on HE and observed increased hyporheic residence time and downwelling flux rate at local and reach scales. The authors reported that the induced morphological changes had greater effect on hyporheic flows than boulders alone, concreting the influence of secondary bedform presented by Gordon *et al.* (2013). Model limitations and simplification were reported in both Zhou & Endreny (2013) and Dudunake *et al.* (2020) studies.

Few studies have attempted to provide a process-based understanding of in-channel restoration structures on HEF (Hester & Doyle 2008; Crispell & Endreny 2009; Wade *et al.* 2020). Crispell & Endreny (2009) conducted field experiments on a third order stream, Greene County, NY, USA, using thermal sensors to study the influence of J-hook and cross-vane structures. They observed that with increase in discharge, HEF changed around the structure and streambed slope was the controlling factor. Hester & Doyle (2008) chose a simplified hypothetical stream to comprehend the impact of weirs, steps and lateral structures and concluded that structure size, background groundwater discharge and hydraulic conductivity

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(HC) were the primary factors controlling HEF, while channel slope and baseflow discharge was relatively less important. Among the structures, weirs were most effective followed by steps and then lateral structures in inducing HEF. Both the studies were influenced by the work of Rosgen (2001), who had assessed different structures in case of stream stabilization and river restoration and both the studies were limited in rigorous evaluation of features due to 1D modelling. Wade *et al.* (2020) researched Beaver Dam Analogues (BDA), an artificially constructed permeable structure to promote hydraulic head differentials to induce exchanges, in a third order Red Canyon Creek near Lander, Wyoming, USA. The authors observed higher vertical fluxes, zones of spatially varying nitrate production and anaerobic reduction. The authors also reported that exchanges were enhanced only after a certain structure height was crossed and that it had little influence on surface water chemistry.

Modelling studies were valuable to deduce the complex hyporheic processes induced by streambed features. Boano *et al.* (2010) applied numerical simulations to investigate the influence of river sinuosity in spatial distribution of chemicals involved in redox reactions and their temporal variation due to meander evolution. A steady state supply of single dissolved organic compound was assumed to be supplied from stream to HZ. The authors reported that the neck and apex region of the meander had slowest and quickest hyporheic flowpaths, which also determined the limits of reaction timescale. Azinheira *et al.* (2014) and Hester *et al.* (2016) modelled a restored stream stretch of Blacksburg, Virginia, USA to analyze the performance of in-stream structures and inset floodplains in solute retention and nitrate removal under different flow conditions. Azinheira *et al.* (2014) observed that in-stream structure retained solutes during the summer baseflow scenario while the floodplains retained it during stormflow conditions. Hyporheic residence time in an in-stream structure was three to five times larger than in the floodplain and performed better in the case of nitrate removal, but was not enough to influence water quality via biochemical reactions. The reaction was transport limited as the rate of induced HEF was low, whereas nitrate removal in floodplains was reaction limited; that is, nitrogen uptake limited (Hester *et al.* 2016). Neither of the structures was engaged throughout the year nor could they be engaged simultaneously, resulting in limited solute retention and nitrate removal. Yang *et al.* (2018) used a reactive transport model to quantify the effects of dam-induced hydrodynamics on biogeochemical transformations of chromate (Cr) in Columbia River in Washington State, USA. The authors reported that flow direction reversals caused by the dam influenced the rate and extent of pollutant transformation depending upon dissolved and particulate organic carbon supplied by the stream. Monofy & Boano (2021) prepared a synthetic coupled surface-ground water model of Maruia River, New Zealand, to quantify the influences of streamflow, groundwater and sediment anisotropy on HZ characteristics due to fully developed alternate bars. They observed the existence of two HZs, shallow and deep, influenced by surface water and groundwater variations respectively, and sediment anisotropy further enhanced it. The authors also proposed a predictive model to predict HZ flux, residence time and depths based on bar submergence, surrounding groundwater and anisotropy of sediments. Summary of the literature on surface modification features is presented in Table 1.

Subsurface feature modification

While surface features were more intended for stream restoration than creating hyporheic flux (Herzog *et al.* 2016), subsurface features were typically engineered to enhance hyporheic exchanges (Ward *et al.* 2011). These modifications are related to the applied changes in the streambed subsurface like alteration of HC of streambed sediments, or introduction of subsurface structures or direct modifications of the HZ (Ward *et al.* 2011; Herzog *et al.* 2018; Peter *et al.* 2019) resulting in HEF enhancements. Vaux (1968) was first to purpose introduction of engineered structures with varying HC in the shallow subsurface to enhance hyporheic exchanges (Ward *et al.* 2011). Robertson & Merkley (2009) reported few reviews of initial studies on streambed modification for nitrate removal from agricultural drainages; it included use of tiled drains, constructed wetlands, end-to-pipe bioreactors and denitrification walls.

Ward *et al.* (2011) revisited the original proposals made by Vaux (1968) and prepared numerical models of the conceptual structures to study hyporheic flux and residence time induced by it. The results exhibited that structures with high HC converged flowpaths towards and through the structures while low HC structures deflected them. The authors also suggested suitable structure type, material, length and height to implement based on the restoration, design and residence time objectives. They further quoted that the structural design results were applicable to natural features and the results could be used for design of subsurface component of traditional restoration structures. The study was conducted in 2D space with homogeneous and isotropic sediment condition, which resulted in simplified flowpaths. While Ward *et al.* (2011) evaluated the structural performance keeping the field conditions like slope and insitu HC constant, Herzog *et al.* (2016) explored more

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Table 1 | Summary of surface feature modification studies

Author	Modification feature	Type of study	Objective	Methodology
Kasahara & Hill (2006)	Riffle and step	Field	Nitrate removal	Tracer studies
Kasahara & Hill (2007)	Gravel bar and re-meandered stream	Field	Nitrate removal	Tracer studies
Mutz *et al.* (2007)	Instream wood	Flume	Evaluate vertical exchanges	Tracer studies
Tonina & Buffington (2007)	Gravel pool-riffle channel	Flume	Extent of hyporheic exchanges	Tracers and modelling
Hester & Doyle (2008)	Weirs, steps and lateral structure	Conceptual model	Evaluation of structural influence on HEF	Modelling using field data
Crispell & Endreny (2009)	Cross vane and J-hook rock structure	Conceptual model	Evaluation of structural influence on HEF	Modelling using temperature data
Boano *et al.* (2010)	Evolving meanders	Numerical modelling	Spatial distribution of chemical species	Morphodynamic model, Hyporheic Flow model and Biogeochemical model
Zarnetske *et al.* (2011)	Gravel bar	Field	Nitrification and denitrification in HZ	Tracer studies
Gordon *et al.* (2013)	Rock cross-vane structure	Field	Magnitude of HEF and its effect on stream ecosystem	Thermal and chemical data and modelling
Zhou & Endreny (2013)	Channel spanning cobbles over pool riffle bedform	Flume	To quantify exchange rates and its variation with channel discharge	Tracer, thermal data and modelling
Azinheira *et al.* (2014)	Cross-vane and inset floodplain	Conceptual Model	To evaluate induced exchanges during different seasons	Modelling using Field Data
Hester *et al.* (2016)	Weirs and inset floodplain	Conceptual Model	Nitrate removal in different seasons	Modelling using Field Data
Yang *et al.* (2018)	Dams	Model	Chromate {Cr(VI)} transformation	Modelling using Field Data
Doughty *et al.* (2020)	Channel-spanning logjam	Field	Quantify HEF response	Tracers, electrical resistivity (ER) imaging
Dudunake *et al.* (2020)	Boulders	Flume	Quantify Hyporheic Exchanges	Modelling
Wade *et al.* (2020)	Beaver dam analogues	Field	Monitor HE flux and biogeochemistry	Temperature profiles, field sampling
Monofy & Boano (2021)	Alternate bars	Modelling	Quantify variations in HZ characteristics	Coupled surface water-groundwater model

complex model and its sensitivity to varying insitu HC and slope condition, as they believed that these variables could also be manipulated in case of large restoration projects. A conceptual model of a constructed stream facility was prepared to analyze the modified streambed structures, termed as Biohydrochemical Enhancement Structures for Stormwater Treatment (BEST) for their suitability in varying insitu HC and slope settings, concerning removal of metals, E.coli, nitrogen and phosphorus. The authors observed that combination of high and low HC structures placed together were best suited for pollutant removal and recommended that incorporation of geomedia into restoration structures would further enhance the reaction rates and make the structures more efficient. They reported that the modules were most appropriate for urban streams, which received inputs from stormwater runoff and recycled water, but would not be feasible in streams with high silt loads.

Lab-scale flume experiments have been successfully used to study the bedform influence and sediment characteristics on HEF, bacterial diversity and pollutant transformations (Kunkel & Radke 2008, 2011; Nodler *et al.* 2014; Li *et al.* 2015; Jaeger

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et al. 2019). Flume mesocosms are best suited for investigating micropollutant degradation process due to its small-scale exchanges and short flow paths (Zarnetske *et al.* 2011; Jaeger *et al.* 2019; Schaper *et al.* 2019) and it also bridges the gap between field and batch experiments (Jaeger *et al.* 2019). Recirculating flumes have been used (Kunkel & Radke 2008; Li *et al.* 2015) more than one at a time (Jaeger *et al.* 2019, 2021; Cook *et al.* 2020) to investigate HC and transformation relations, bacterial diversity and flow influence on degradation half-lives and bedform feature modulations, sediment size influence on biofilm communities. Results showed that bacterial diversity in the sediment and their size had paramount effect on micropollutant degradation (Jaeger *et al.* 2019; Cook *et al.* 2020; Betterle *et al.* 2021) and risk of secondary contamination due to transformed products was high (Li *et al.* 2015). Higher bacterial diversity was inversely related to hyporheic flux (Betterle *et al.* 2021) due to biofilm clogging, but could be resolved by larger bedform structures (Cook *et al.* 2020). Although direct extrapolation of results to real systems is complicated due to simplification in laboratory experiment, flume studies delivered important insights into micropollutant transformation processes and their product formation in the HZ (Li *et al.* 2015; Jaeger *et al.* 2019).

Field studies on application of constructed HZ was reported by Robertson & Merkley (2009), Herzog *et al.* (2018), Peter *et al.* (2019) and Bakke *et al.* (2020). Each individual study varied in all aspects from construction to its objective of application. While Robertson & Merkley (2009) constructed an instream bioreactor in a first order agricultural stream in southern Ontario, Canada, for nitrate removal, Herzog *et al.* (2018) performed outdoor flume studies using smart tracers (resazurin) in a constructed stream facility in Colorado, USA to test BEST structures for induced hyporheic exchange and reactive solute attenuation. Both the studies used woodchips as geomedia for increasing reaction rates and are the only known field experimentation of engineered HZ incorporated with geomedia. The coarse media of woodchips provided high permeability in subsurface allowing for higher flow through rates, even for small hydraulic head drop (Robertson & Merkley 2009). The bioreactor was constructed in an agricultural ditch with variable height outlet pipe to control flow rate. Nitrate removal rates were greater than in constructed wetland and depended directly on flow rate and atmospheric temperature. The BEST structure achieved 54% more hyporheic transient storage and required 55% less length than the control structure to remove 1-log of the reactive tracer, resazurin. Herzog *et al.* (2018) suggested that the BEST structure was best suited for low-discharge streams in urban catchments and stormwater channels with flow modulation. Although both designs offered definite advantage in induced hyporheic exchanges and the use of geomedia for pollutant removal was an added benefit, problems like colmation reduced the efficiency of the bioreactor over time and would also have affected the performance of BEST structures, if tested.

Peter *et al.* (2019) designed and implemented the first direct HZ manipulations in an urban stream channel in Seattle, Washington, USA. The authors determined the fate of commonly found urban water contaminants in the EHZ, which they defined as Hyporheic Design Element (HDE). A year later, Bakke *et al.* (2020) published a similar streambed engineering study in the same channel, focused on the design and performance of the constructed HZ in inducing hyporheic exchanges. The design features incorporated for both studies were use of channel-spanning logs to create a plunge pool, barrier, excavation of HZ and backfill with clean gravel. While the logs and barriers forced the water parcel lower, which increased flowpath lengths/residence times, the backfill increased the hyporheic exchange capacity. Peter *et al.* (2019) used dye and tracers to determine hyporheic flowpaths and achieved greater than 50% removal of pollutants in flow paths with more than three hours of residence time. Bakke *et al.* (2020) relied on temperature mapping, tracer studies to determine flux and reported that the vertical flux had increased by 89%, hyporheic volume by three fold and that the engineered element maintained the natural scour and fill during the duration of the study. Summary of the subsurface feature modification studies is given in Table 2.

DISCUSSION

Feature modifications

The reviewed literatures explored various vertical (riffle-step, channel-spanning logjams, boulders, dams, BDAs, weirs and partially channel spanning cross-vanes and J-hook) and lateral (gravel bars, alternate bars and meanders) flux inducing features in the case of EHZ exchanges. Kasahara & Hill (2007) reported that exchange rates induced were similar for both types of features, but vertical flux inducing structures were more efficient in nitrate removal based on their smaller size. Full channel spanning structures induced larger vertical flux and promoted exchanges than partially spanning structures (Hester & Doyle 2008) while partial structures could serve an important role in benthic life sustenance and help in ecosystem

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Table 2 | Summary of subsurface feature modification studies

Author	Modification feature	Type of study	Objective	Methodology
Robertson & Merkley (2009)	Instream bioreactor	Field	Nitrate removal	Field sampling
Ward *et al.* (2011)	Varying HC structures	Modelling	Evaluation of structural influence on HEF	Numerical modelling
Herzog *et al.* (2016)	BEST structure	Conceptual modelling	Induced exchanges and pollutant removal	Data from constructed stream facility
Herzog *et al.* (2018)	BEST module with geomedia	Outdoor flume	Induced exchanges and solute removal	Tracers, field data and modelling
Jaeger *et al.* (2019)	Bedform undulations	Flume	Influence of HEF and bacterial diversity in micropollutant degradation	Salt tracers and sampling
Peter *et al.* (2019)	Direct HZ modification- HDE	Field	Removal of pharmaceuticals	Tracers and field sampling
Bakke *et al.* (2020)	Direct HZ modification	Field	Maximize induced HZ and residence time	Tracers, temperature sensors and field data
Cook *et al.* (2020)	Undulating bedform	Flume	Influence of biofilm growth and bedform interaction on HE	Tracers and sampling
Betterle *et al.* (2021)	Undulating bedform	Flume	Influence of bacterial diversity and sediment morphology on HE	Salt tracers, hydrodynamic model

management (Crispell & Endreny 2009; Gordon *et al.* 2013). Although subsurface modifications were not explored as much as its counterpart (Tables 1 and 2) (Hester *et al.* 2018), yet they held definitive advantages over surface features which included control over residence timescales, minimal effect on geomorphology, aquatic life and surface water temperatures (Ward *et al.* 2011; Herzog *et al.* 2016; Hester *et al.* 2018).

Most of the studies reviewed focused on exploration of HEF induced by individual structures. While such individual feature studies were important for general understanding of hyporheic processes at local scale, it did not reflect their ability on overall water quality improvements (Morén *et al.* 2017). Moreover, restoration practitioners usually assessed water quality targets at reach or catchment scale (Hester & Gooseff 2011; Morén *et al.* 2017; Hester *et al.* 2018), highlighting the need for reach scale multiple feature studies (Morén *et al.* 2017; Hester *et al.* 2018). Few studies compared the engineered interventions to natural morphological features (Smidt *et al.* 2015; Morén *et al.* 2017; Hester *et al.* 2018) and reported higher overall flux induced due to engineered structures. Recent studies at bedform scale have highlighted the importance of streambed heterogeneity, bed and width undulations in case of hyporheic response to modification studies (Liu *et al.* 2020; Movahedi *et al.* 2021) where the sediment architecture was often more influential than channel morphology in case of highly heterogeneous streambeds (Liu *et al.* 2020). Advancement in computing capabilities enabled numerical simulation and optimization studies of design structures (rock-vanes, weirs) for stream restoration and enhanced nitrogen removal (Khosronejad *et al.* 2018; Liu & Chui 2020).

Few authors have addressed the need for long-term assessment of restoration structures (Lewandowski *et al.* 2019). Drummond *et al.* (2018) assessed hyporheic exchanges in restored and unrestored reach nine years post restoration. The authors observed restored reaches had greater exchanges of fine particles and was not affected by clogging, rather scouring of fine particles was taking place. Mayer *et al.* (2021) presented a detailed long-term assessment from 2002-2012 of geomorphic stream restoration features on nitrogen(N) transport and transformation and observed progressive reductions in N content in restored reaches over the years. The authors reported that some engineered structures fared better at regulating N levels while other eroded post restoration. Morley *et al.* (2021) assessed EHZ aided floodplain restoration on microbial response at three paired stream reaches from 2014 to 2017. The authors observed fall of water temperatures, increased particulate organic matter (POM) and dissolved organic carbon (DOC) concentrations, shifts in microbial compositions and increased hyporheic invertebrate densities and richness.

Methodology selection

The selection of appropriate methodology was governed by the attributes being evaluated, type of outcome desired, its spatiotemporal extent and the cost and effort available (Bakke *et al.* 2020). Numerous approaches (Tables 1 and 2) has been

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adopted to quantify the effects of modified features on complex physical and biochemical processes (Betterle *et al.* 2021). Kalbus *et al.* (2006) and Brunner *et al.* (2017) provided an overview of different measuring and modelling techniques in determination of HEF. Lewandowski *et al.* (2019) reported that each methodology adopted had its own advantages and limitations. While field investigation provided the best realistic conditions, it lacked in control of environmental factors. Flume studies could control environmental factors, but efforts required was higher. Numerical models could achieve in-depth assessment of hyporheic processes, isolate environmental factors and predict future outcomes, but were limited by assumptions, accuracy of measured data and system feedback to applied changes (Dudunake *et al.* 2020). Jaeger *et al.* (2019) suggested adoption of a multi-feature, multidisciplinary approach of study to reduce inadequacies and maximize research outputs.

Lewandowski *et al.* (2019) reported availability of numerous in-stream tracers in flume and field studies of HZs (salt tracers, heat tracer, which includes an active heat pulse and fiber optics-based sensors, radioactive gas tracers and smart tracers). Of these, only a few have been explored in EHZ studies such as salt traces (Kasahara & Hill 2006, 2007), heat sensors (Crispell & Endreny 2009; Gordon *et al.* 2013; Bakke *et al.* 2020), smart tracers like resazurin-resorufin for microbial activity determination (Herzog *et al.* 2018) and fluorescence tracer (Mutz *et al.* 2007; Drummond *et al.* 2018). It was reported that temperature-based studies were the most suitable methodology in HZ studies as it was a robust, quick, easy and inexpensive parameter to measure (Kalbus *et al.* 2006; Lewandowski *et al.* 2019). High spatiotemporal measurements of temperature using emerging technologies such as advance heat pulse sensors and fiber optics (Lawrence *et al.* 2013; Lewandowski *et al.* 2019), further added to its benefits. Although extensively used, tracers could only capture the net solute transport, provide empirical rather than process based estimates and could not indicate exact locations of flux change or the factors influencing it (Lautz & Siegel 2006).

Numerical modelling of groundwater flows addresses the shortcomings of tracer-based studies and could bridge the gap between filed observations and characterization of hyporheic processes (Lautz & Siegel 2006). The extensive improvements in computational capabilities coupled with advancement in fluid dynamics algorithms have broadened the path for refined study of complex hyporheic processes and have proven to be powerful tools in groundwater flow studies (Betterle *et al.* 2021). Groundwater flow models allow for simulation and quantification of gross effects of hyporheic processes, including area of flux change, residence times, and flux rates (Lautz & Siegel 2006) and recently, the role of microbial diversity (Betterle *et al.* 2021). A wide range of numerical models is available for study of groundwater flows and their selection processes have been thoroughly reviewed by Kumar (2019). While numerical models have been successful in studying induced exchanges, they neglect the effect of structural heterogeneity, downstream variability and streambed dynamics, known to influence flux rates, residence time and flowpaths. (Cardenas *et al.* 2004; Ward & Packman 2018; Liu *et al.* 2020). Limitations like assumption of constant model parameters, spatial homogeneity and stationary bedform dynamics prevent upscaling of modelling results into predictions at larger scale (Ward 2016; Liu & Chui 2018). Further, numerical studies lacked accountability of feedback from engineered structures on streambed morphological changes due to sediment transport (Dudunake *et al.* 2020).

Laboratory and outdoor flumes have been useful for investigating drivers of hyporheic processes as they enable control over environmental factors, thus reducing variability in the system (Betterle *et al.* 2021). Flume mesocosms are a valuable tool in linking control of lab experiments to originality of field experiments (Jaeger *et al.* 2019). However, research in flume studies have rarely considered bed movements (Lewandowski *et al.* 2019) although their relevance has been long mentioned (Elliott & Brooks 1997a, 1997b). Recent literatures have been trying to address such limits, as Liu & Chui (2018) quantified the effect of streambed heterogeneity and anisotropy on residence time (RT) and observed that it reduced the mean RT. Marttila *et al.* (2019) reported that the addition of sand (fine sediments) in gravel beds had a negative effect on hyporheic flux. Liu *et al.* (2020) observed that heterogeneous sediments with high sorptive capacity compressed the mixing zones and Betterle *et al.* (2021) reported that high bacterial diversity in sediments also reduced the hyporheic flux.

Limitations

For the hyporheic processes to occur in the HZ, physical, microbial, and biochemical parts are equally important (Ward *et al.* 2011; Ward 2016). However, the necessary environment to drive the microbial and biochemical processes is provided by the hydrodynamic conditions created by the features (Battin 1999, 2000; Ward *et al.* 2011) and is the focus area of this review. Although the multidisciplinary understanding of the complex and dynamic surface and subsurface water interactions have improved in recent decades (Conant *et al.* 2019) but it still lacked, the framework to predict complex interactions, manage and transfer knowledge at reach or larger scale (Ward 2016; Magliozzi *et al.* 2018; Reeder *et al.* 2018; Ward & Packman 2018; Conant *et al.* 2019). Further, the detailed understanding of role of biodiversity (Marmonier *et al.* 2012), multi-instream

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structural influence (Hester *et al.* 2018) and long-term effects of stream restorations (Mayer *et al.* 2021) on HEF and transformations were limited. Below are some of the major limitations observed in EHZ studies:

- All the studies undertaken were at local, sub-reach or reach scale.
- Most of the studies were concentrated on individual structural influence on HEF.
- Simplification like spatial homogeneity, steady hydrologic conditions and stationary bedforms in the case of flume and modelling studies.
- Studies on the influence of induced exchanges on biological and chemical processes is limited.
- EHZ applications are limited to agricultural and urban streams.

Research gaps

- EHZ studies have been limited to local and reach scales, their explorations at channel and catchment scales is still missing (Magliozzi *et al.* 2018).
- Influence of integrated surface subsurface features and multi structural features on hyporheic exchanges were not explored (Ward *et al.* 2011; Hester *et al.* 2018).
- Nitrate removal rates, microbial activity and dissolved oxygen (DO) in water are regulated by stream temperatures, which depend upon ambient air temperatures (Robertson & Merkley 2009; Zarnetske *et al.* 2011; Lawrence *et al.* 2013). Thus, atmospheric temperature is an important variable to be considered in flume and field studies.
- Many authors have suggested use of geomedia to enhance reaction rates such as biochar woodchips, recycled industrial materials (Robertson & Merkley 2009; Herzog *et al.* 2016, 2018; Peter *et al.* 2019), of which only woodchips has been tested in EHZ studies (Robertson & Merkley 2009; Herzog *et al.* 2018).
- Accounting for feedbacks, streambed heterogeneity and dynamics in modelling studies (Liu & Chui 2018; Dudunake *et al.* 2020).
- Exploration of EHZ management practices on aquatic life (Marmonier *et al.* 2012).

Future scope of EHZ studies for stream restoration

The field of EHZ applications in water quality and habitat improvement is still young (Lawrence *et al.* 2013) with all the treatment processes in the experimental stage (Bakke *et al.* 2020). There is still a large gap between the current stage of knowledge and management activities in the case of EHZ applications (Morén *et al.* 2017; Ward & Packman 2018). Although methodological advances and use of innovative technologies (Lewandowski *et al.* 2019) in recent decades have vastly reduced this gap, it is still far from being significant to restoration managers (Morén *et al.* 2017). Limitations like lack of proper design guidelines to quantify hyporheic processes, which reflect water quality improvements at decision-making scales (Morén *et al.* 2017), hinders its adaptation. Some immediate future scope in EHZ studies can be listed as:

- Studies need to correlate the extent of restoration required with significant water quality benefits desired at reach and higher scales.
- A holistic study of hyporheic processes and impacts which integrates multi-disciplinary knowledge at channel and catchment scales.
- Investigations of integrated design approach of surface and subsurface structures to maximize HEF.
- Standardization of frameworks for conceptualization of surface water and groundwater interactions at each of local, reach, and catchment scales.
- Scope of EHZs can be explored in artificial channels, as low-cost post-effluent treatment units for water reclamation can be a valuable addition to water conservation and management practices.

CONCLUSION

This review assembled a comprehensive overview of the design and applications of EHZ in stream health improvement. Each individual research reviewed, unique and specific to some predefined objectives, not only imparted some valuable insights on EHZ processes and controls but also underlined some major limitations in its applications. Though subsurface structures had potential benefits with little effect on stream temperature, geomorphology and aquatic life, it was not explored as much as surface features nor was any literature on integrated structures available. Numerous approaches were undertaken to quantify the effects of engineered features, field, laboratory, and modelling, which all had their pros and cons, with thermal monitoring

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based field studies being most suitable with quick, robust and inexpensive heat sensors. Flumes provided convenience of controlling environmental parameters to isolate controlling factors and numerical models allowed for conceptualization, simulation, optimization and prediction of exchanges at different scales.

Rivers are not isolated systems but interact continuously with surrounding floodplains and underlying aquifers (Magliozzi *et al.* 2018). Developing an understanding of these interactions and their influences on water quality, quantity, and ecosystem health can provide the basis for land and water management and conservation of the environment (Conant *et al.* 2019). Under the stress of accelerated climate change and anthropogenic activities (Boano *et al.* 2014), it becomes imperative to consider integrated approaches for sustainable management of water resources (Wu *et al.* 2020). HZ research provides such opportunity by drawing researchers from various backgrounds to exchange ideas, knowledge and technologies to maintain and conserve land, water and related resources (Krause *et al.* 2011). Although there is potential in EHZ applications to make its way to standard restorations practices, yet it is important to note that EHZ is just one part of a comprehensive management strategy for river restoration and its application alone cannot improve the stream health (Lewandowski *et al.* 2019).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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