Chapter

The Hyporheic Zone

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Abstract

This chapter introduces the key concepts of the hyporheic zone. It considers the research context in terms of the Water Framework Directive and the breadth of literature associated with the hyporheic zone. The interplay between hydrological, chemical and biological processes is explained, and a range of different approaches to field sampling and monitoring are described. A framework for considering the factors contributing to the conceptualisation of the hyporheic zone is presented, with an emphasis on the importance of understanding streambed sediments and their architecture to assess hydraulic functioning and modelling of the hyporheic zone. The hyporheic zone in karst catchments is also given specific consideration. Returning to the theme of linked hydrological, biological and chemical processes, the results of two case studies demonstrate the value of integrating hydrological measurements with geochemistry in order to elucidate hyporheic zone functioning.

Keywords: surface water groundwater interaction, hyporheic zone, monitoring

1. Introduction

1.1 Aims and objectives

The aim of this chapter is to consider the hydrology of the hyporheic zone in the context of the hydrological cycle. The chapter starts, the chapter starts with a description of the definitions of, and reasons for studying, the hyporheic zone, then goes on to consider sampling and measurement techniques followed by a consideration of the assessment and applications of this data and understanding. The results of two case studies provide examples of research approaches and technique. The case studies show how integrating hydrological measurements with geochemistry assists in the elucidation of hyporheic zone functioning.

1.2 Definitions and significance

The hyporheic zone is the term given to the subsurface interface between surface and groundwater bodies. It is most commonly considered in the context of streams (or rivers) interfacing with groundwater. Groundwater in this context is the water that fills the spaces between soil particles and fractured rock that comprises the saturated ground that extends beneath the water table and the overlying unsaturated zone. Cardenas [1] suggests that the hyporheic zone is synonymous with the transient storage zone of earlier literature, i.e. including bank storage within the riparian zone (broadly defined as the interface between land and a river or stream), e.g. Bencala and Walters [2]. As it is a zone of flux between ground- and surface water, there are hydrological, ecological and hydrogeological responses that characterise the hyporheic zone. Reflecting the range of perspectives, there are differing definitions of the hyporheic zone. Hydrologically it is conceptualised as the proportion of flow that occurs in permeable streambed deposits upon which channel flow occurs. This can also be seen as the component of flow that cannot be measured using conventional flow monitoring techniques. The sediments in this zone have an important role in influencing the distribution of permeability in the hyporheic zone attributable to grain size distribution, source rock and architecture, as related to topography, river dynamics and climate [3] and modified by biological and chemical processes. Orghidan [4] recognised the ecological significance of the hyporheic zone with the introduction of the term "hyporheic corridor concept". One difficulty for the ecologist is defining the thickness of the hyporheic zone. For example, they can delineate it by the occurrence of hyporheobiont life stages or by the extent of riverine animals [5]. The definition favoured by Brunke and Gonser [6] is that the hyporheic zone is distinguished from groundwater and stream water by demonstrating characteristics of both, with different gradients to each. Clearly the hyporheic zone is dynamic as a consequence of changing hydraulic conditions and seasonality, and this is recognised by ecologists in the term "dynamic ecotone" [5]. The hydrogeologist's view of the hyporheic zone is as part of the groundwater system, because it comprises subsurface water within the saturated zone.

As a concept, the hyporheic zone is important in addressing integrated catchment modelling and management. In Europe the Water Framework Directive (2000) provides the context for an increased research interest in the hyporheic zone [7], because it promotes the management of groundwater bodies and surface water bodies in an integrated way, requiring that (hydraulic) pathways between the two are understood. Analysis of the connectivity of surface and groundwater in conjunction with other protected areas such as designated wetland is a specific requirement of the River Basin Catchment Plan [5]. The ability to assess mass flux across the groundwater-surface water interface, predict attenuation processes in this zone, link hyporheic and benthic chemical conditions and ecological health and develop reliable and transferable conceptual models of flow and attenuation defines the requirements of conceptual understanding.

Soil properties impose a strong influence on the dynamics of the hyporheic zone in terms of transient storage and retention. The transient storage capacity of the hyporheic zone can be important in accounting for apparent losses or gains in water balance calculations, e.g. Lapworth et al. [8], which may inform resource evaluation studies. Improved understanding of the spatial components of the hyporheic zone offers significant potential in terms of understanding the process of flood migration along the length of the stream in the context of catchment scale flood modelling and management. Hydrologically, the hyporheic zone is an important component of some poorly understood karst systems (e.g. turloughs or estavelles), wetlands and lake environments. More recently, in the context of urban environments, the concept of the hyporheic zone has been extended to include the impacts of leaking pipes contributing water of different chemistry to the zone of transient storage or service ducts providing preferential pathways, perched water tables and altered flow and groundwater conditions, e.g. Bricker et al. [9].

Within the hyporheic zone, the geology, hydrology, hydrochemistry and biology exhibit feedbacks and dependencies. Consequently, hydrological understanding is important to the aspects of hyporheic zone research that embrace the ecological and chemical benefits (ecosystem services) of the zone. Broadly, hyporheic faunal communities vary with the environmental conditions, including hydrology, climate, geology, sedimentary architecture, land use and chemical conditions (natural and anthropogenic). The influence of hydrological flux in the hyporheic zone is particularly important in defining nutrient (carbon) distribution and its upward and downward movement and consequently the distribution of the ecotones that impose structure on the hyporheic communities (hyporheos, including benthic, epigean and phreatic species) and their distribution in the sediment [10, 11]. For example, during periods of environmental stress, typically marked by drought or flood, the hyporheic zone provides a place of refuge for some stream-dwelling species. Other species permanently occupy the hyporheic zone niche. In some streams, the hyporheic zone species extend in excess of 100 m beneath the streambed, e.g. [12]; elsewhere they occur at relatively shallow depths. There have been a number of associated shifts in understanding relating to the discovery of hyporheic invertebrates and the concept of the hyporheos as an indicator of ecological health. Furthermore, the broad range of biological species, including microbial fauna, has an important role in contaminant attenuation, and this defines the zone as an ecosystem service with a potential to mitigate contaminants. Whilst there is an extensive literature associated with this topic, it lies beyond the remit of this chapter.

In conjunction with a range of biological processes, the geochemistry of the hyporheic zone provides a valuable natural system for the remediation of a range of contaminants. For example, this zone is particularly important in hosting denitrification processes. There are a number of factors that contribute to the geochemistry of the hyporheic zone, including bedrock geology, superficial geology, water residence time, oxygen concentrations, the degree of mixing of ground- and surface water, pH conditions and breakdown of contaminants, including plastic and the organic content. Additionally, bedrock textures may be important for the growth of specific precipitates. Its attenuation capacity varies with its thickness and permeability. This potential has been recognised in the context of the remediation of the legacy of abandoned mines in the UK [13].

2. Research methods: hydrological measurements and sampling in the hyporheic zone

As with any other system, sampling and monitoring of the hyporheic zone requires a strategy and plan [14], the formulation of which requires a clear understanding of the reason for monitoring and what it aims to achieve. This is particularly relevant in the context of the hyporheic zone where, if it is required, it may be possible, with careful planning, to optimise sampling to derive hydrological, ecological and hydrogeochemical data in conjunction with each other. The second step in the development of a sampling strategy is the completion of a desk-based study of the area of interest. Ideally, this should be undertaken at the catchment scale to understand the broader hydrological context with subsequent more detailed studies at the sub-catchment, reach and project scale. As well as considering the spatial scale of interest, decisions will have to be made regarding the temporal aspects of data collection: how frequently will data be collected and how long will the monitoring continue in order to characterise the flow regime, chemical and biological context? Subsequent decisions will relate to how to undertake the monitoring or sampling and whether it should comprise point methods, averaging methods or distributed methods to provide insight into spatial or temporal variation [14]. Key factors influencing the frequency, duration and type of monitoring include the funding that is available, site access and health and safety considerations as well as the scientific factors, such as the nature of geology proposed for sampling. Streambeds with rock or coarse sediments in their base are inherently more challenging than finer sediment-bedded streams. A selection of potential sampling methods is detailed in **Table 1**. In selecting appropriate sampling and monitoring

Method	Description	Hydrological	Ecological	Hydrogeochemical
Seepage meter [15]	Measures exchange of water across the sediment–water interface	Y		
Wells and sampling pits	Can be used for sediment characterisation as well as constructing access for water sampling. Can also be used for hydraulic testing (e.g. falling or rising head tests; slug tests). The sampling zone of a well is dictated by the positioning of the sample points, e.g. well screen	Y		Y
Mini drive-point piezometers [16]	Used to enhance understanding of head and hydrochemistry (see case studies)	Y		Y
Natural tracers including temperature and electrolytic conductivity	Measurement of temperature as a tracer of flow paths. Care needed to ensure that readings are not affected by sampling materials, if measured in a piezometer or multilevel sampler	Y		
Physicochemical parameters as a proxy for hydrochemical zoning	pH, temperature, electrolytic conductivity, dissolved oxygen and redox probes			Y
Diffusive equilibrium in thin films (DET), Byrne et al. [17], or diffuse gradient in thin films [18]	In situ passive sampling of porewater by diffusive equilibrium in thin films. Stainless steel cover containing DET gel			Y
Net sampling	Can be lowered into wells or natural water bodies		Y	
Kick sampling [19]	Standard method in qualitative studies of macroinvertebrates		Y	
Pump sampling [20]	Another method for qualitative studies of macroinvertebrates		Y	
Automatic sampling	Automatic samplers can be programmed to take periodic samples, e.g. to sample through a weather event such as a storm		Y	Y
Kubiena tin or similar	Used for undisturbed sampling of sediment for resin moisture replacement and optical examination of hydrogeological properties	Y		
Geotechnical soil property tests	For geotechnical characterisation of the alluvium, might include density, grading, porosity, field capacity, hydraulic conductivity, moisture content and electrical resistivity	Y		

Method	Description	Hydrological	Ecological	Hydrogeochemical
Geophysical testing [21]	Field-based electrical resistivity can be used in monitoring contaminant plumes or tracers such as salt, as well as monitoring changes in moisture content and the position of the water table	Y		Y

Table 1.
A range of potential sampling/monitoring methods.

techniques, construction materials and their potential to impact results should be considered; for example, whilst robust, the use of galvanised steel products can give rise to artificially high concentrations of zinc.

Catchment scale analysis of the topography, land use, geology, hydrogeology and water features, as well as any hydrological data, will provide an evidence base for assessing potential zones of groundwater-surface water interaction and possible access points to the stream. Typically, hydrological studies focus on the flux and determination of the gradients between the surface and groundwater; therefore, they will largely focus on head, seepage, changes in stream discharge, permeability and hydraulic conductivity. This will require measurements in the subsurface, in the hyporheic zone and in the stream. Wherever possible measurement techniques should be selected to provide complimentary data and optimise confidence in the results.

Traditionally, flow regimes within a single river system were measured using flow-gauging techniques, typically using impeller or electromagnetic current meters [22]. However, whilst these techniques are valuable in identifying zones of potential loss or gain in discharge for further investigation, they preclude measurement of flow in the hyporheic zone; therefore, different or additional techniques are required for monitoring the hyporheic zone. Three-dimensional temperature has been found to be a valuable parameter for characterising the hyporheic zone [23, 24]. This is because the longer the groundwater is in contact with bedrock, the more it will equilibrate with the bedrock temperature, whereas surface water will tend to equilibrate with atmospheric conditions. The rates of temperature exchange are affected by the depth of the river, the thickness and permeability of the river sediment, the characteristics of the upper part of the bedrock and the specific heat capacities of the bedrock and sediments. These effects vary both seasonally and in response to hydrological events such as flooding or, for example, releases of dam water [24, 25].

Tracing experiments provide the advection and dispersion characteristics of the transient storage zone that are required for modelling [26]. Conservative tracers, such as sodium chloride, sodium bromide and rhodamine WT are well-established techniques in the analysis of hydrological characteristics of streams [27, 28]. Others have included natural tracers such as radon [29]. Additionally, there are a number of emerging, anthropogenically introduced conservative tracers; for example, Möller et al. [30] used gadolinium. Other contaminants can be utilised as tracers to demonstrate the extent of the hyporheic zone or the extent of change in the hyporheic zone, e.g. Ciszewski and Aleksander-Kwaterczak [31] used the concentrations of zinc and cadmium in the sediment and waters of Baila Przemsza River in southern Poland to define the extent of mining-induced alteration of the hyporheic zone. However, consideration will need to be given to the geochemistry of the contaminants if they are non-conservative and are being used to provide information on permeability and flow.

Streambed geology and sediment characterisation are required for the effective design of field experiments, hydrological modelling and effective river basin management. In the first instance, this information can come from reconnaissance visits and remote sensing data. However, more in-depth understanding of the processes and sediment sorting patterns is important for hydraulic modelling, because the distribution of sediments influences the boundary roughness and geochemistry. This may require specialist sediment sampling techniques at the site scale or techniques such as airborne LiDAR, in conjunction with geomorphological modelling [32] at the reach or catchment scale. Remote sensing technologies offer the advantage of providing remote access to areas of restricted ground access which potentially offers a new opportunity to start to undertake higher-resolution stream sediment mapping, for example, as undertaken by Miklin and Galia [33]. Geomorphological mapping of this type offers the potential to predict the lateral extent of the hyporheic zone in areas where active channel migration occurs.

3. Analysis

3.1 Hydrological characterisation

Fundamental to researching the hydrology of the hyporheic zone is the development of the conceptual understanding of the host system. A conceptual model is necessary to facilitate targeting of the dominant hyporheic zone processes at the catchment or reach-scale. This requires understanding of the underlying catchment characteristics including land use, the climate and meteorology, geology and geomorphology. Whilst stream hydrology can be considered in terms of catchment recharge, throughflow and discharge (or infiltration, surface run-off, interflow and base-flow), flooding, seasonality and environmental interaction (including anthropogenic factors), extension to the hyporheic zone requires greater consideration of the bed sediments and the hydrological exchange processes therein. For example, in the UK, the Centre for Ecology and Hydrology (CEH) Integrated Hydrological Digital Terrain Model derives outputs for flood modelling based on the range of catchment parameters presented in **Table 2**. Using the CEH approach, it is implicit that the hydrology of soil type (HOST, [34]) parameters embrace the hyporheic zone and that the catchment parameters reflect both the stream hydrology and the

Catchment parameter	Description
AREA	Catchment drainage area
BFI HOST	A base-flow index derived from the hydrological properties of soils as detailed in the HOST dataset, which is based on soil types at a 1-km grid [34]
CENTROID; DPLBAR	Modelling descriptors: centroid of the catchment; distance between model nodes
DPSBAR	Mean drainage path slope as an indicator of catchment steepness
FARL	Potential for flood attenuation by reservoirs and lakes
FPEXT	Extent of the floodplain
LDP	Longest drainage path
PROPWET	A catchment wetness index
SAAR	Average rainfall over a standard period
SMD	Mean soil moisture deficit for the standard period
SPRHOST	Standard percentage run-off of each soil type
URBEXT	Extent of urban and suburban land cover

Table 2.
The primary catchment parameters used for flood estimation by the Centre for Ecology and Hydrology.

stream bedforms at both the catchment and reach scale. However, this model does not allow for geomorphological nuances of the stream sediments and underlying geology that are fundamental to understanding hyporheic exchange. Stream bedforms and their sediments are commonly a product of current, historic and geological climatic conditions. Typically in the UK, drainage patterns and stream sediments reflect the legacy of climatic change throughout the Quaternary, and as a consequence the average bed load grain size may exceed that of the current hydrological conditions of the river or stream, i.e. stream under-fit.

In the UK, sediments deposited in upland catchments are dominated by braided streams that are graded from cobbles in the higher reaches, to gravel and sand in the lower reaches [35, 36]. In lower alluvial floodplains, meandering rivers commonly occupy larger floodplains within which channel migration occurs and the sediments are dominated by sand silt and clay-grade particles. Within each of these environments, stream geomorphology influences the distribution of sediments, e.g. formation of point bars on the inner bank of meander bends. As well as the large-scale lithological variations observed in point bar deposits [37], there are smaller-scale variations, whereby mud-prone sediment is interbedded with sand-prone sediment as inclined heterolithic strata [38]. These complex internal heterolithic variations are particularly important when considering circumstances where chute channels may traverse the point bar deposit because the internal architecture of the hyporheic zone could be more complex and its lateral extent altered. Fine-grained counter point bars may occur on the outer bank of the meander bend where the bend becomes convex in shape [39]. These deposits baffle throughflow due to their fine-grained nature and contrast with eddy-accretion deposits, in turn characterised by thick, sand-prone accumulations [40, 41], which would more easily encourage throughflow. These local variations in permeability affect streambed biogeochemistry and the potential lateral and vertical extents of the hyporheic zone.

The hydraulic connectivity of streams and groundwater can also be considered at the catchment scale and conceptualised in terms of losing and gaining stretches of the stream, where a gaining reach is one that is supplemented by groundwater and a losing reach is one where a proportion of the stream water recharges the underlying aquifer [42]. Perennial streams losing stretches of perennial streams are in constant continuity with groundwater, whereas continuity of gaining stretches may vary with groundwater levels, unless continuity is maintained by switching from gaining to losing conditions. Gaining and losing reaches can be defined from the relationship between stream water level and the potentiometric surface of the groundwater or by changes in the stream discharge, unless subject to artificial modification. The zones of recharge and discharge from the streambed are likely to migrate in accordance with the hydraulic conditions, e.g. due to flooding or seasonality. In many streams the area of discharge or recharge is not evenly distributed across the streambed, which may be due to head differences, differences in hydraulic conductivity or the structure and composition of the streambed sediments.

Hyporheic zone flow paths can be both diffuse and focused. Diffuse flow will reflect the matrix permeability, whereas focused flow may comprise bypass flow that utilises macropores and pipes in the unsaturated zone [43, 44]. The bedrock geology and sediment source zones are reflected in the properties of the hyporheic zone sediments, whilst the form or geomorphology of the sediments reflects the hydraulic setting and its influence on sediment distribution [45]. Flow rates fluctuate around a meander bend, whereby stronger currents are observed at the outer bank and weaker flow is observed on the inner bank [46]. In meandering fluvial systems where alluvium is accreted onto point bar deposits, the finer-grade alluvium is deposited on the inner bank of the downstream limb of the bend, whereas the coarser-grade alluvium is deposited at, and upstream of, the meander apex [37, 47].

The variation in grain size distribution within the sediments gives rise to variability in flow of water through the deposits; more mud-prone sediment has lower porosity and permeability than more sand-prone sediment. The fluctuating flow rates around a meander bend lead to reach-scale variations in sediment-bedded stream hydrological processes commonly leading to the formation of pool and riffle bedforms. Pools are associated with fast, turbulent flow, and consequently the streambed at the pool is comprised of coarse grains up to pebble and cobble calibre [48], which may make these areas proficient in enabling throughflow of water. There is an inverse relationship between both relative pool depth and distance between pools and increasing channel gradient [49]. Generally, the riffles are points of down welling or infiltration at the upstream or stoss side and discharge at the crest or lee side of the riffle [1, 2, 5, 27]. However, the catchment context can result in exceptions to this, e.g. Magliozzi et al. [50].

Streambed permeability is susceptible to modification by other factors, such as the chemical processes that give rise to dissolution or precipitation [51], physical sedimentation and clogging (colmation) and biofilm formation and modification by the streambed fauna. Chen et al. [52] established that influent groundwater flow paths are associated with fine sediment removal from the sediment matrix, thereby increasing the near-surface hydraulic conductivity, whereas downward entrainment of fine particles resulting in siltation or clogging of the sediment in zones of effluent flow (losing reaches of a stream) is associated with a reduction in permeability. For the Nebraskan example described by Chen et al. [52], the alterations to the streambed permeability extended to depths of 5 m or more.

Bypass flow, also termed "preferential" or "fast" flow, is transmitted at orders of magnitude greater than the Darcian matrix flow. Soil pipes are the largest category of macropore and can form connected networks [53]; they have been defined as macropores that are sufficiently large for water to sculpt their form [54]. Soil erosion by throughflow of water gives rise to conduits for lateral or vertical flow [44]. The maximum diameter that a pipe can reach without collapsing will be determined by the density, structure and grain size of the sediment. Piping is most common in the hyporheic zone in bank sediments, locations where surface water is focused by the topography and also where groundwater is focused in gaining reaches of a stream.

The hyporheic zone is related to the base-flow by the residence time, which can be measured using tracers [55]. Investigating a mountain stream at an "Experimental Forest" in Oregon, Haggerty et al. [55] characterised the residence time from a tracer breakthrough curve with a long-tail, poorly characterised by an exponential model and indicative of a large range of exchange timescales, each associated with different volumes of water. This would seem to be representative of many sediment-bedded streams with ranges in permeability and hydraulic regimes. The hyporheic zone also responds to seasonality and importantly for stream ecology, may extend the wet season of ephemeral stream reaches and continue to provide base-flow after the surface stream appears to have "dried up".

Flooding can affect the hyporheic zone causing a hydraulic response as flood waters extend into it. The response is scale dependent and is greater where the channel is unconstrained [56]. In unconstrained systems where channel changes occur, morphological change in the channel may result in localised steepening of the hydraulic gradient or abandonment of hyporheic zones associated with abandoned channels [56, 57]. As the flooding recedes and base-flow re-establishes, the volume of the hyporheic zone will adjust to the new conditions, which has implications for shifts in the stream ecology. During flooding, the increased velocity of surface water can impact the hyporheic zone in accordance with the Venturi Effect. This comprises a net pressure decrease as a function of water velocity, thereby

Factor	Characterising data requirements
Hydrological	Precipitation; temperature; variation with aspect, temporal and seasonal variability (changing spatial and vertical distribution of the hyporheic zone); flooding and catchment parameters (**Table 1**)
Topographical	Slope gradients and lengths, aspect, relationship of sub-catchments to catchments and reach-scale representation
Scale	Regional, catchment, reach or geomorphological feature
Hydrogeological	Head, seepages seasonality as indicated by storativity and head change, permeability and transmissivity at all scales
Geological	Bedrock and superficial lithologies, geological structure, weathering and erosion history, alluvial sediment thickness and architecture and sediment mobility
Valley type	Degree of channel confinement and stream connectivity, upland versus lowland channels, longitudinal and lateral valley gradients, distribution of in-channel bedforms and bank conditions
Vegetation	Types of vegetation: in-channel and riparian and their influence on the hydrology in terms of water balance, hydrogeochemistry and hydrology, e.g. Reynolds number
Urbanisation	Culverted drainage inputs, hydrological changes due to sustainable urban drainage scheme implementation, hard and soft engineering impact on channel characteristics [59] and ecological impacts (biological and chemical)
Climate	Potential climate change impacts, e. g. impacts on existing conditions [60], and climatic zone analogues, e.g. Peel et al. [61]
Biogeochemical and ecohydrological	Chemical and biological characteristics and diversity, nutrient potential, organic matter content and habitats

Table 3.
Factors to consider in catchment scale hyporheic zone modelling.

potentially giving rise to a local reversal in the hydraulic gradient and influx of deeper groundwater [58], despite the higher river stage. Understanding exchanges of this type is particularly important in the characterisation of the hyporheic zone for the management of flood risk.

Hyporheic zone hydrology research scales range from catchment to valley or reach scale. Fully integrated catchment scale modelling and management requires catchment through valley and reach-scale understanding of the hyporheic zone exchange [50]. The key factors underpinning such an analysis correspond with the requirements for conceptual modelling detailed above and summarised in **Table 3**. Each of these factors is subject to scaling issues and time-dependent variability. The range in the scale of hyporheic exchange flows also impacts the attenuating and ecological benefits that are derived from the hyporheic zone in different zones within a catchment. For example, a system dominated by groundwater recharge through coarse sediments may mask the potential hydrochemical benefits afforded by pools and riffles. This complexity is additional to the broader understanding of gaining and losing stretches of the stream or river and is informed by detailed bedform architecture as related to geomorphological processes and described above. Additionally, there are temporal and climatic variations that are fundamental to understanding the functioning of the hyporheic zone.

There are numerous modelling approaches that reflect the multifaceted nature of the hyporheic zone, including ground- and surface water flux and biological and chemical gradients. Hydrological modelling can incorporate the hyporheic zone as a single storage component (e.g. [62]) with fractal scales of response (ranges of permeability and flow path lengths) accounting for the very long tail in the hydrograph

(Haggerty et al., [55]). Alternatively, attempts have been made to model both the relative stationarity of surface water in the main channel and the transient storage (characterised by advection and dispersion) in the stagnant zones separately, e.g. Kazezyilmaz-Alhan and Medina [26].

Further research is required to understand the long-term impacts of environmental change on the hyporheic zone. Undoubtedly the hyporheic zone is susceptible to environmental change (climate and anthropogenic impacts) leading to chemical changes, such as pH change or the addition of contaminants. However, global recognition of the value of the hyporheic zone suggests that, although subject to modification, the value of the hyporheic zone will continue in the context of climate change. For example, it is important in both Arctic streams [27] and tropical streams [63]. Therefore it is likely that the hyporheic zone will be increasingly valued in the context of climate change, because of its buffering capacity (hydrological, chemical and ecological), particularly in the light of forecasts of temperature extremes and higher-intensity rainfall and consequential flooding events.

Increased urbanisation is associated with a decrease in stream base-flow [64]. This is, in part, a consequence of hard engineering, with both consequential reduction in recharge to the hyporheic zone and occlusion of its discharge zones. This in turn, reduces the buffering for flood events, leading to higher flood levels and a need for increased levels of engineering to push flood waters through urban environments as quickly as possible. This urban reduction in stream base-flow reduces the calibre of alluvium accumulating on the streambed, baffling circulation of water between the stream and the hyporheic zone, which in turn reduces the overall water capacity of the system by reducing bank and streambed storage and potentially increasing flood risk. Additionally, increased plastic sedimentation in urban areas may prevent circulation altogether by forming an impermeable barrier. The susceptibility of the ecology of the hyporheic zone to environmental change adds further to the pressure on its hydrological functioning, e.g. algal blooms increase the potential for colmation. The hydrological functioning of the hyporheic zone may also be affected by natural processes such as changes to bedrock weathering and geomorphological processes that affect bank stability. Whilst bedrock susceptibility and geomorphology vary with rock type and hydrological conditions, they tend towards reducing the permeability of the hyporheic zone by the addition of sediment to the streambed, whereas flooding events have the potential to remobilise and transport sediment.

3.2 Hyporheic zones in karst environments

Karst aquifers warrant separate consideration in the context of their hydrological functioning. It is widely recognised that water-mixing zones can be the focus for karst processes within a karst system [65]; therefore, the hyporheic zone is likely to be an important zone within a karstic system. In practice, in many karst aquifers, the hyporheic zone is particularly difficult to define. This is attributed to (i) the difficulty accessing karst systems owing to the range of pore sizes and the difficulty in predicting their distribution, (ii) the rapid change in contact between surface water and groundwater in karst environment, (iii) the water table is commonly poorly defined and (iv) the complexity of some karst systems, e.g. the interplay of matrix and karst porosity in weakly karstic systems, such as chalk [8]. However, the significance of the hyporheic zone in karst systems should not be overlooked particularly with respect to hydraulic function and because of its vulnerability to contamination, attenuation potential and contribution to the evolution of karst systems [65], as well as its ecological value [66].

Karst systems primarily develop their porosity and permeability and therefore their flow paths through dissolution. Dissolution is commonly focused on structural [67], lithological or geochemical boundaries in the lithology, e.g. inception horizons [68]. If, over geological timescales, the hydrological conditions change, the relict karst systems may be abandoned or only partially functioning in the context of the current hydrological regime of a karst aquifer. Furthermore karst systems can form as tiers that are hydrologically focused on different catchment scales, e.g. base level of the major catchment and base level of a sub-catchment, i.e. a losing tributary river. This has the potential to extend the hyporheic zone of a karst system to a considerable depth in some karstic aquifers and makes it difficult to define the groundwater table of karstic aquifers. Characteristically karst aquifers exhibit low storage and therefore seasonally larger changes in head- than matrix-dominated aquifer with higher storage; thus, the hydraulic conditions are variable, and it is difficult to monitor and quantify hyporheic zone processes, particularly when they occur over the very short timescales that are characteristic of more "flashy" catchments.

Humid tropical karst is characterised by limestone hills (towers or pinnacles). Tower karst development appears to be related to the presences of massive crystalline limestone and the development of a system of open, steeply dipping joints that have been exploited by meteoric and shallow groundwater associated with either current or past climatic regimes. Twidale [69] argues that the pinnacles are the consequence of subsurface-weathering fronts and that weathering has been achieved by deep phreatic waters retained in a regolith. Associated with the pinnacles are a succession of notches, comprising sub-horizontal, laterally, solutionally enlarged conduit systems. It is suspected that these are indicative of Pleistocene interglacial high sea levels at elevations of tens of metres above the current sea level, and it has been suggested that they are formed by swamp waters and that subsoil solution may be associated with the formation of cliff foot caves. Without being explicit in the literature, these formational processes are clearly associated with the hyporheic zone. Further evidence of the significance of the hyporheic zone in karst processes comes from progressive increases in the base-flow index towards the lower end of karst streams. Whilst, traditionally, speleogenesis has been conceptualised from the hydrogeological perspective of source, throughflow and discharge with the independent flow paths of the unsaturated zone becoming more ordered at the "water table". Diffusely recharged water in karst aquifers with long residence times is quickly saturated by carbonate [65], even with the addition of carbon dioxide derived from vegetation or the pH change attributable to overlying acid-generating soils, suggesting that an additional process is required for dissolutional enlargement at the discharge end of the system. Gulley et al. [70] in their investigation of the less mature karst systems of the Suwannee River in North-Central Florida established that undersaturated floodwater-related dissolution during flow reversal in the hyporheic zone of karst discharge areas likely accounts for a significant component of the dissolutional enlargement at the downstream end of the flow path. Additionally, exchange between different scales of conduit contributes to attenuation of contaminants in this zone. More specifically, flood water-dispersed contaminants will be displaced by distal groundwater as the floodwater recedes, thereby contributing to dilution.

Flood waters are also responsible for the delivery of sediment via the hyporheic zone into karst systems, and this has a significant role in the armouring of portions of the karst aquifer and attenuation of contaminants [71], but is prone to disturbance by subsequent flooding. Similarly, algal armouring of conduit surfaces is sustained by nutrient supplied by hyporheic exchange. The processes that take place in the hyporheic zone of karst aquifers occur at a range of scales from that of a conduit-wall topography, e.g. scallops to large-scale conduit networks. Arguably, rapid exchange over shorter flow paths [72] is probably the most hydrologically significant type of hyporheic zone impact on karst aquifers, because of the greater potential for dissolution resulting from rapid water exchange. However, this is a relatively new research area, and interplay with delivery of soils gases and carbon storage (e.g. [73, 74]) may place this in a different perspective in the longer term.

Two additional aspects of the hyporheic zone have evolved from karst research. Firstly, the relative independence of karst flow paths has led some authors to consider karst conduits as being analogous to surface streams and therefore suggest that karst conduit hyporheic zones can be characterised (e.g. [75]). Whilst this is undoubtedly true because of the influence on biology, contaminant attenuation, geochemistry and speleogenesis of karst systems, such an approach is likely to lead to unnecessary ambiguity in hyporheic zone research. Secondly, the extensive research on the use of tracers to identify flow paths in karst aquifer provides a rich resource in terms of understanding the availability, benefits and challenges associated with a broad range of techniques, e.g. Smart [28].

4. Results from case studies

The two case studies presented below comprise accounts of research that have been undertaken by the British Geological Survey to further understanding of the hydrogeochemical functioning and value of the hyporheic zone in the context of groundwater contamination. Other British Geological Survey research projects include research on the role of the hyporheic zone in flooding in Oxford [76] and Lambourne [8] in Southern England and Eddleston, Scotland [77].

4.1 Rookhope Burn, wear sub-catchment of Northumbria River Basin District, Northern England

This case study was focused on the Rookhope Burn, an upland stream forming a tributary of the River Wear in northern England. Here the potential for attenuation in the hyporheic zone was explored because the stream lies within a significantly mine-impacted area of the North Pennines Orefield, UK. Zinc had been identified as the contaminant of concern. Mass balances of in-stream and in-flow (subsurface, historic mine working related, contributions of zinc-contaminated groundwater) chemical loads determined from major and trace elements concentrations and synoptic flow monitoring had identified sinks as well as sources of zinc in the burn. The sources comprise rising, mining-contaminated groundwater [78] with the potential to shift the hyporheic zone [56].

In order to investigate this further, the physicochemical composition of the hyporheic zone, a stream stretch, was characterised at two contrasting flow and temperature regimes [13]. The Rookhope Burn streambed comprises coarse-textured river terrace deposits. The underlying bedrock geology is formed of mineralised Dinantian limestones capped by Namurian sandstones and mudstones. For this catchment vertical element concentration gradients were obtained using multilevel samplers down to a depth of 40 cm below the water-sediment boundary and along a 12-m reach. Additionally, in situ diffuse gradients in thin film (DGT) measurements of surface water and porewater were obtained (**Figure 1**).

The multilevel samplers described by Dearden and Palumbo-Roe [18], like those used at Polmadie Burn and described below, comprised a 12 mm ID 1200 mm long, HDPE pipe, fitted at one end with a stainless steel drive-point to enable penetration of the device into sediments. The pipe had two 4-mm-diameter holes at the base

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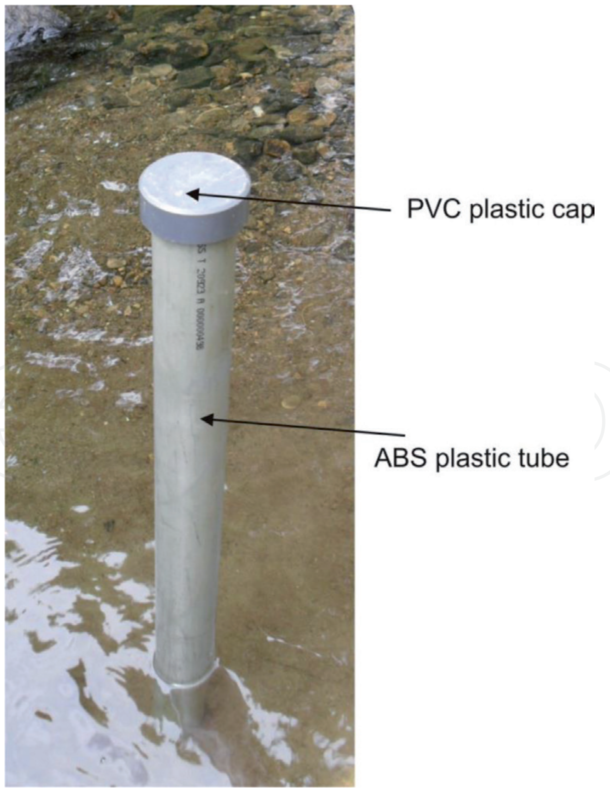

Figure 1.
DGT placed in the base of the hollow sampler and left for 24 hours.

to allow the piezometric surface within the hyporheic zone to be monitored. Four discrete 1.6 mm ID Teflon sampling tubes were attached around the central pipe and were terminated such that ports were located at 10-cm intervals. Each of the ports was encased in (45 μm) nylon mesh screen to prevent sediment blockages. Porewater samples were recovered using a low-flow multichannel peristaltic pump that enabled simultaneous sampling of the four ports at an approximate flow rate of 4 mL/min; pH and Eh were measured using a flow-through cell, and Pt electrode Eh-measured values were corrected to the standard hydrogen electrode. The level of the hyporheic zone water was measured relative to the river water level using a mini dipper placed down the central HDPE tube [13].

Two sampling surveys were undertaken, one in the summer (July 2010) and one in the autumn (October 2010). The hydrological conditions in the catchment were very consistent for at least 10 days before each sampling event. In addition to the multilevel samples, samples of surface water were collected at each of the four locations. Groundwater was also collected from a private well adjacent to the sampling site for comparison with the hyporheic porewaters [13].

Near neutral pH and oxidising conditions characterised the hyporheic zone. The upper 15–20 cm was dominated by the chemistry of the overlying water, whilst interactions with the solid phase occurred in the deeper part of the hyporheic zone. Mineralogical analysis of manganese-rich grain coatings from the bed sediment indicated that manganese was being attenuated in the hyporheic zone. Additionally, there was clear evidence for hyporheic porewater enrichment in lead that was unaffected seasonally, whilst zinc concentrations were higher in July. The significance of the observed sediment-scale hyporheic processes on the reach-scale geochemical mass balance was estimated by using surface water geochemical loading calculations. Along a 700-m stream stretch of the burn, a constant loss of manganese stream load and continuous gain of lead stream load with more temporally variable zinc stream loading were measured. This demonstrated that the hyporheic zone of the mine-impacted stream supports steep manganese, lead and zinc gradients. Seasonality in the hyporheic zone was suspected from the results, but was not fully investigated, and therefore further investigation of seasonality was identified as a necessary future research direction for this catchment. More specifically, this would require periods of continuous monitoring, which is difficult to establish in remote catchments.

4.2 Polmadie Burn, Clyde catchment, Scotland

The potential for hyporheic zone attenuation of chromium contamination in Polmadie Burn, a minor tributary of the River Clyde in Scotland, UK, was investigated during two monitoring periods in February and September 2012 [79]. A summary of the monitoring techniques and findings are presented here to demonstrate the importance of linking hydrology to geochemical assessments of the context of hyporheic zone.

The Polmadie Burn is an urban steam, in the order of 3 km to the south-east of Glasgow City Centre. It is impacted by hexavalent chromium-rich effluent leached from the landfilled residue from historical (late nineteenth and early twentieth century) processing of chromite ore [80]. The stream responds rapidly to changes in the discharge from its culverted urban drainage catchment. The underlying Carboniferous bedrock comprises cyclic sequences of mudstone, siltstone and sandstone that are overlain by superficial deposits of river terrace deposits capped by low-permeability alluvium. The low permeability of the hyporheic zone contrasts with the coarse streambed investigated at Rookhope.

Following a desk study investigation of the burn, a sampling strategy was designed to integrate hydrology and geochemistry in the context of spatial and temporal change. A specific aspect of the investigation was the attention given to the health and safety issues associated with working in the chromium-contaminated stream with a soft silty streambed (**Figure 2**). Upstream and downstream transects were selected for sampling, which included in situ monitoring via multilevel minipoint piezometers (**Figure 2**), hydraulic testing (falling head slug tests in the bank sediments) as well as sampling and geochemical/mineralogical characterisation of hyporheic water, surface water and streambed sediments. At each transect the multilevel piezometers comprised a number of carefully labelled sampling ports to facilitate hydraulic gradient determination and vertical profile sampling from within the bed sediments at depths of up to 90 cm below bed level. Following a stabilisation period of 12 hours, sampling was undertaken with a low-flow multichannel peristaltic pump. The fieldwork comprised two campaigns to monitor the hyporheic zone processes in operation at different stages of the stream. The February visit allowed sampling of water from the hyporheic zone and stream over a large short-term variation in stream depth, which comprised a low tide during which there was temporary exposure of river bed sediments followed by overnight rainfall and high stream levels. The second field visit, in September, coincided with more constant hydraulic conditions. This allowed synoptic surface water quality sampling to be carried out to provide qualitative evidence of any whole-stream-contaminant attenuation to which the hyporheic zone may contribute.

Detrital grains of historical chromium process residue were found to contribute to the total chromium concentrations (size fraction < 150 μm) that reached 8800 mg kg^{-1} in the streambed sediment. There was a sharp decrease of total dissolved (filtered < 0.45 μm) chromium concentrations at the surface water-sediment boundary in all profiles, from a mean chromium concentration of 1100 μg l^{-1} in the surface water to 5 μg l^{-1} in the porewater. This was associated with an elevated ferrous iron concentration in the porewater (mean concentration 1700 μg l^{-1}) and chromium (VI) reduction to chromium (III) solids of low solubility. However, the hyporheic zone did not respond to the large short-term changes of stream stage as indicated by

Figure 2.
Hyporheic zone multilevel sampling of the bed of Polmadie Burn, Glasgow. Note how, for ease of access, the multipoint sampling tubes were extended from the sampling point to the base station where the peristaltic pump was deployed.

the hyporheic zone water composition. It was concluded that the low-permeability alluvial sediments imposed a limit on the effectiveness of the hyporheic zone for enhancing Cr surface water quality at the reach scale. This was also evident in the surface water quality synoptic sampling which showed only moderate to low downstream decreases in surface water chromium concentrations. Thus, the key finding was that although the geochemical potential for hyporheic attenuation of surface water chromium was clearly established, the hydraulic functioning of the hyporheic zone was limited by poor hydrological connectivity with the Polmadie Burn.

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