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Hyporheic Zone: *In Situ* Sampling

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ABSTRACT: The hyporheic zone (HZ) is a fundamental part of a river ecosystem. It is the zone of interaction between groundwater and channel water. Movement of channel water and groundwater occurs through changes in hydraulic pressure and occurs at multiple scales. The HZ generally contains higher chemical concentrations and lower dissolved oxygen levels than the channel due to lower rates of exchange, lack of sunlight and longer residence times. Organisms residing in this zone are known as the hyporheos, and can also include benthic invertebrates dwelling there temporarily for refugia, or as part of a life cycle. Research in this area may involve sampling invertebrate distribution and abundance, flow dynamics between and within the HZ and channel, hydrochemistry of the HZ and characterisation of the substrate. Common sampling techniques for these areas of research involve coring, tracing and *in situ* extraction. This article briefly introduces these techniques, with primary focus on *in situ* extraction, in particular pump sampling, which is an effective method for monitoring hydrochemistry.

KEYWORDS: pump sampling; freeze coring; hyporheos; Bou-Rouch; hydrochemistry; interstitial water

Introduction

Defining the Hyporheic Zone

The hyporheic zone (HZ) is a highly dynamic region, loosely defined as the saturated interstitial sediment below the streambed and adjacent riverbanks where exchange of channel water and groundwater occurs (White, 1993; Figure 1). This definition reflects three decades of a gradual inclusion of the HZ into fluvial research, since early recognition of its importance (e.g. Orghidan, 1959; Schwoerbel, 1961; Williams and Hynes, 1974).

Until the late 1980s, there was a focus on defining the extent of the HZ, rather than looking at its functional significance or characteristics. Definition was based mainly on invertebrate sampling (e.g. Schowerbel, 1961; Williams and Hynes, 1974; Williams, 1989), by the distribution of surface and subsurface organisms and their lateral and vertical extents (Boulton *et al*., 2010). It was expressed in the late 1980s that there are a large number of factors that control the HZ, as well as the distribution of invertebrates themselves, rendering this sampling strategy insufficient (e.g. Danielopol, 1989; White, 1993).

This recognition led to a number of investigations into the physicochemical properties of the HZ (e.g. Triska *et al*., 1989), attempting to distinguish groundwater and channel water contributions to subsurface regions. Gibert *et al*. (1990) further developed our understanding of the HZ, describing its role as a “dynamic ecotone”. The boundaries of this ecotone are likely to change temporally and spatially with response to hydrological behaviour and characteristics of the sediment (Gibert *et al*., 1990; Boulton *et al*., 2010; Williams *et al*., 2010). Vervier *et al*. (1992) concluded that a HZ depended on the elasticity, permeability, biodiversity and connectivity of the ecotone. This pushed focus towards its functional significance, both ecologically and hydrologically, and its influence on the surface stream (Boulton *et al*., 2010).

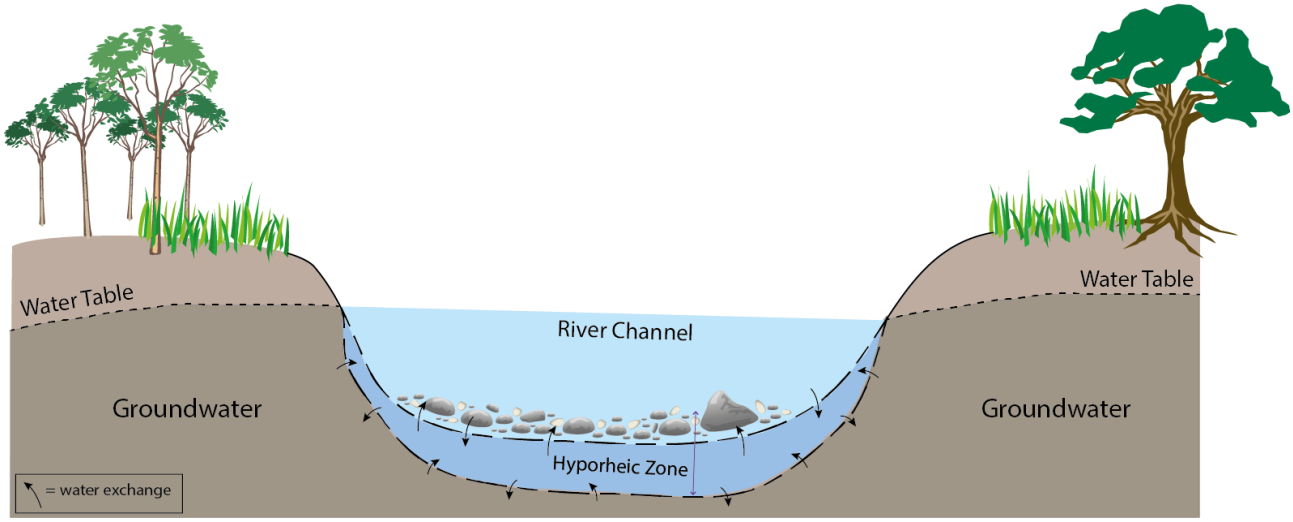

Figure 1: The approximate position of the hyporheic zone from a cross-sectional view of a river catchment. Typically considered to extend between a few centimetres to a few metres in size (Stanford and Ward, 1988).

Characteristics of the Hyporheic Zone

The exchange of water between a surface stream and the HZ is governed by pressure differences at multiple scales (Wondzell, 2006; Boulton, 2007; Boulton *et al*., 2010). At the catchment scale, exchange occurs when there are differences in stream and groundwater levels. At a smaller, reach scale, interactions between channel flow and geomorphological features create pressure variations, such as slope, riffle-pool sequences (Elliott and Brooks, 1997) and step sequences (Kasahara and Wondzell, 2003). A common pressure difference can be found along a riffle (Figure 2); shallowing of channel water at the head of a riffle creates higher pressures, causing downwelling of surface waters into the interstitial areas. Deepening of the water at the tail end of the riffle produces lower pressures, causing upwelling of groundwater into the surface stream (Wondzell, 2006; Boulton, 2007).

The channel water and groundwater that combine to make up the interstitial water of the HZ have characteristic differences. In a healthy channel the water is typically clean, oxygenated, has variable discharge, short residence times and changing physicochemical conditions (Boulton *et al*., 1998). In contrast, groundwater is often characterised by long residence times in the surrounding catchment, with chemically reducing conditions that can decrease dissolved oxygen levels, bring high chemical concentrations and lower the temperature (Soulsby *et al*., 2001; Malcolm *et al*., 2004). The combination of these waters vary temporally, due to changes in water depth and catchment water levels, and spatially, due to changes in channel morphology (Malcolm *et al*., 2004).

Invertebrate communities living in the HZ are known as the hyporheos, and include permanent and semi-permanent inhabitants (Williams and Hynes, 1974; Stubbington, 2012). The differences in hydrochemistry between the HZ and channel, and within the HZ itself, have a broader significance with regard to the organisms that dwell in this zone temporarily. The HZ has been recognised as a place of refugia, for example during times of drought, extreme flows, or high levels of pollution (Williams and Hynes, 1974; Dole-Olivier *et al*., 1997; Wood *et al*., 2010; Stubbington *et al*., 2011; Stubbington, 2012; Crossman *et al*., 2012). Organisms may also use the HZ as a refuge during vulnerable stages of their life cycle, a prime example are salmonid eggs. Much hyporheic research has focused on the survival of salmonid eggs in redds constructed in gravel-bed rivers (e.g. Soulsby *et al*., 2001; Geist *et al*., 2002; Malcolm *et al*., 2004, 2010).

A number of sampling techniques have been developed, using a variety of methods, to try to better understand the interactions and habitat preferences of the hyporheos, the dynamics of hydrochemistry, and the level of influence that the HZ has on stream health.

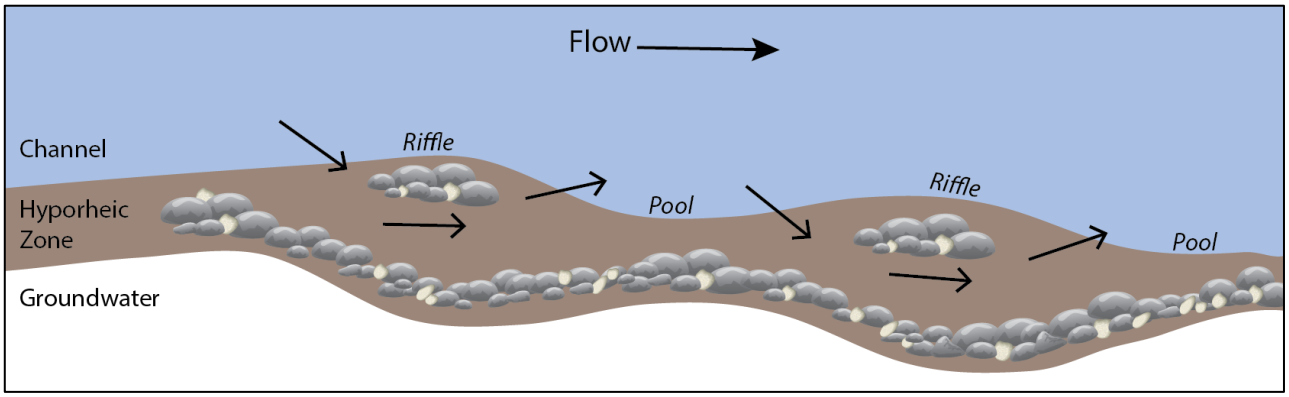

Figure 2: Directional flow of water through riffle-pool sequences in the hyporheic zone. Arrows indicate regions of downwelling and upwelling due to changes in hydraulic pressure.

Sampling the Hyporheic Zone

Overview of Sampling Techniques

Sampling the HZ is difficult, because it is relatively inaccessible and a fragile system (Palmer, 1993). During sampling, the natural conditions of the HZ may be altered and therefore may not provide a true representation (Palmer, 1993). The three main techniques followed for sampling the HZ are coring, tracing, and *in situ* extraction; for each of these techniques there are a variety of methods that can be used. The methods chosen will depend on the research that is being undertaken.

It was suggested by Palmer (1993) that it is best to compare a number of methods to provide better accuracy and precision. Useful comparisons of sampling procedures can be found in Fraser and Williams (1997), Hunt and Stanley (2000), Scarsbrook and Halliday (2002), Dole-Olivier *et al*. (2014) and Tanaka *et al*. (2014). Table 1 summarises relevant literature outlining the HZ methods and associated research themes.

Coring

If examining invertebrate distribution or abundance, it is necessary to sample the natural, undisturbed conditions beneath the bed. For this, a freeze core is often used (e.g. Stocker and Williams, 1972; Pugsley and Hynes, 1983; Adkins and Winterbourn, 1999; Scarsbrook and Halliday, 2002; Nogaro *et al*., 2010; Toran *et al*., 2013), which freezes the sediment and water within the cylinder prior to extraction, including any organism within it. However, there are a number of complications with this method, such as organism escape during disturbance (Bretschko, 1985), or ineffective coring due to the presence of large boulders (Fraser and Williams, 1997; Toran et al., 2013). Another limitation to this method is that it is expensive and labour-intensive (Hunt and Stanley, 2000). An alternative to freeze coring is the use of a standpipe corer (Williams and Hynes, 1974; Franken *et al*., 2001; Storey and Williams, 2004). This involves extracting a core of the bed and immediately storing the sample in sealed containers (Storey and Williams, 2004).

Another coring method that has been developed for research into the hyporheos is the use of colonisation pots (Nelson and Roline, 2003; Crossman *et al*., 2012). These generally consist of cages filled with substrate that attempts to mimic the characteristics of that riverbed. These are submerged into the HZ and left to colonise for a number of weeks (Crossman *et al*., 2012). Upon collection, the baskets are removed and the hyporheos can be analysed. This can be a highly destructive sampling method, as sections of the riverbed must be disturbed during insertion and removal of the cages (Fraser and Williams, 1997; Scarsbrook and Halliday, 2002). There is also no guarantee that the substrate will replicate that of the HZ surrounding it (Fraser and Williams, 1997).

Tracing

If investigating rates of hyporheic water exchange and nutrient processes, tracer experiments are the favoured technique (e.g. Jonsson *et al*., 2003; Wondzell, 2006; Toran *et al*., 2013). In general, these methods involve the injection of one or more non-

Table 1: Examples of studies that have employed the different sampling methods for the main research areas of hyporheic zone science.

	Hydrochemistry	Flow Dynamics	Invertebrate Sampling	Substrate characterisation
Freeze Coring	-	Toran *et al.* (2013)	Pugsley and Hynes (1983); Adkins and Winterbourn (1999); Scarsbrook and Halliday (2002)	Olsen and Townsend (2005); Nogaro *et al*. (2010); Toran *et al*. (2013)
Standpipe Coring	Franken *et al*. (2001)	-	Williams and Hynes (1974); Storey and Williams (2004)	-
Colonisation Pots	-	-	Scarsbrook and Halliday (2002); Nelson and Roline (2003); Crossman *et al*. (2012)	-
Tracers	Jonsson *et al*. (2003); Van Stempvoort *et al*. (2011)	Wondzell (2006); Pinay *et al*. (2009); Birkinshaw and Webb **(**2010); McCallum *et al*. (2012); Toran *et al*. (2013)	-	-
Pump Sampling	Findlay *et al*. (1993); Riss *et al*. (2008); Cornut *et al*. (2012)	-	Hunt and Stanley (2000); Scarsbrook and Halliday (2002)	-
Piezometers	Soulsby *et al*. (2001); Malcolm *et al*. (2004); Hlavacova *et al*. (2005); Lewandowski *et al*. (2011)	Grimaldi and Chaplot (2000); Wondzell (2006); Ibrahim *et al*. (2010)	-	-

reactive tracer into the channel. Wells at specified locations in the riverbed then monitor the travel times or chemical transformations in the HZ (Triska *et al*., 1993; Harvey and Wagner, 2000; Jonsson *et al*., 2003; Pinay *et al*., 2009). Tracers used are often naturally available environmental substances, generally considered to be conservative (Engelhardt *et al*., 2011). These tracers include stable isotopes, chloride (Pinay *et al*., 2009), pharmaceutical compounds (Van Stempvoort *et al*., 2011), and temperature (Birkinshaw and Webb, 2010). Tracer experiments are advantageous against other techniques, in that they can be carried out at larger scales (Harvey *et al*., 1996). However, they are found to be less reliable at flows higher than base levels (Harvey *et al*., 1996).

In situ

In situ extraction is a widely used technique, appropriate for sampling the spatial and/or temporal variation in hyporheic hydrochemistry and invertebrates. *In situ* extraction involves the installation of a permanent or semi-permanent well into the riverbed, either submerged as a piezometer (Hlavacova *et al*., 2005; Ibrahim *et al*., 2010; Lewandowski *et al*., 2011), or reaching the surface of the channel through a rigid tube containing small perforations (Soulsby *et al*., 2001; Cornut *et al*., 2012). These wells then provide an opening from which samples can

be extracted. The remainder of the article will focus on an explanation of *in situ* extraction sampling. For detailed explanations of coring and tracer techniques see *Geomorphological Techniques* Sections 3.11.2 and 3.11.3, respectively.

Common methods for *in situ* sampling the hyporheos follow those developed by Bou and Rouch (1967) and Boulton *et al*. (1992) (e.g. Marmonier *et al*., 1992; Boulton *et al*., 1997, 2003; Hunt and Stanley, 2000; Wood *et al*., 2010; Stubbington *et al*., 2011). This method has also been adapted for sampling the hydrochemistry of the HZ (Findlay *et al*., 1993; Soulsby *et al*., 2001; Youngson *et al*., 2004; Cornut *et al*., 2012). Water and invertebrates are pumped out of the wells by creating a vacuum, and this can then be analysed for hydrochemical properties, invertebrate type, abundance, and diversity. A detailed example of this adapted method, known as pump sampling, is presented in the following case study.

Case study: Water quality of the hyporheic zone in relation to the survival of Freshwater Pearl Mussels, River Esk, North Yorkshire.

The following section describes an example of the pump sampling method, used in a small study of the HZ of the River Esk, North Yorkshire. The aim of the study was to determine reasons for lack of freshwater pearl mussel (*Margaritifera margaritifera)* survival, by looking at comparisons between the hydrochemistry within the HZ and in the channel itself, in varying rates of flow. This can be found in greater detail in Biddulph (2012).

Freshwater pearl mussels are slow-growing molluscs with a complex life cycle (Bauer, 1992). Juvenile mussels spend five years buried beneath the substrate of a riverbed before emerging as mature adults (Geist, 2010). It is at this juvenile stage that they are most vulnerable, as they are very sensitive to changes in water quality (Skinner *et al*., 2003). In the last century the previously large populations of mussels have declined dramatically, with very few signs of recovery (Reid *et al*., 2012).

Freshwater pearl mussels require clean rivers that are low in nutrients (Geist *et al*., 2006), and depend on substratum that is relatively stable and well aerated (Geist and Auerswald, 2007). The main concern around the lack of revival of these mussel populations are the lack of juvenile recruitment (Geist, 2010), so research needs to focus on their habitats during the juvenile stage. A preliminary study was carried out to determine the hyporheic water quality along the mussel-dwelling reach of the River Esk. Sites were selected based on where pearl mussels were known to live, as well as locations where they theoretically could live. Comparable locations were also selected in areas of unsuitable habitat.

A number of pump samplers were constructed (Figure 3), based loosely on those used by Soulsby *et al*. (2001). Hard plastic tubing was used to create wells that were 1 m in length and 2 cm in diameter. Small holes were drilled around the circumference over a length of 20 cm, so that once placed in the riverbed the wells sampled a depth from 10-30 cm below the bed. Augers were used to bore into the riverbed, so that the tubes could be inserted, with a bung in the bottom so that they did not infill with sediment.

When the wells were not in use, a bung was placed in the top (Figure 3b), so that channel water could not enter the tube in periods of high flow. During sampling, a different bung was inserted, containing a narrower, flexible tube running through it and down to the bottom of the well. This tube extended to a one litre bottle, which in turn was connected to a manual vacuum pump (Figure 3a). The vacuum draws water through the perforations in the well, up the narrow tube and into the bottle. One litre of water was drawn up from the HZ, which was then immediately tested for pH, dissolved oxygen (DO), conductivity, temperature and redox potential using a multi-parameter probe. This water was then taken to the laboratory for anion and cation analysis. Sampling took place once a fortnight for six months.

The locations chosen for well installation are important, as hyporheic water quality varies greatly at different points on a riverbed. For this project, the focus was on freshwater pearl mussels, so samples were taken in areas where they are likely to inhabit. A suitable habitat would be at the tail end of a

riffle, where flows are moderate enough to re-oxygenate hyporheic water and reduce sedimentation. This is in contrast to the adjacent deeper pools, where residence time of water in the HZ would be longer, often characterised by lower oxygen levels and higher rates of chemical transformation.

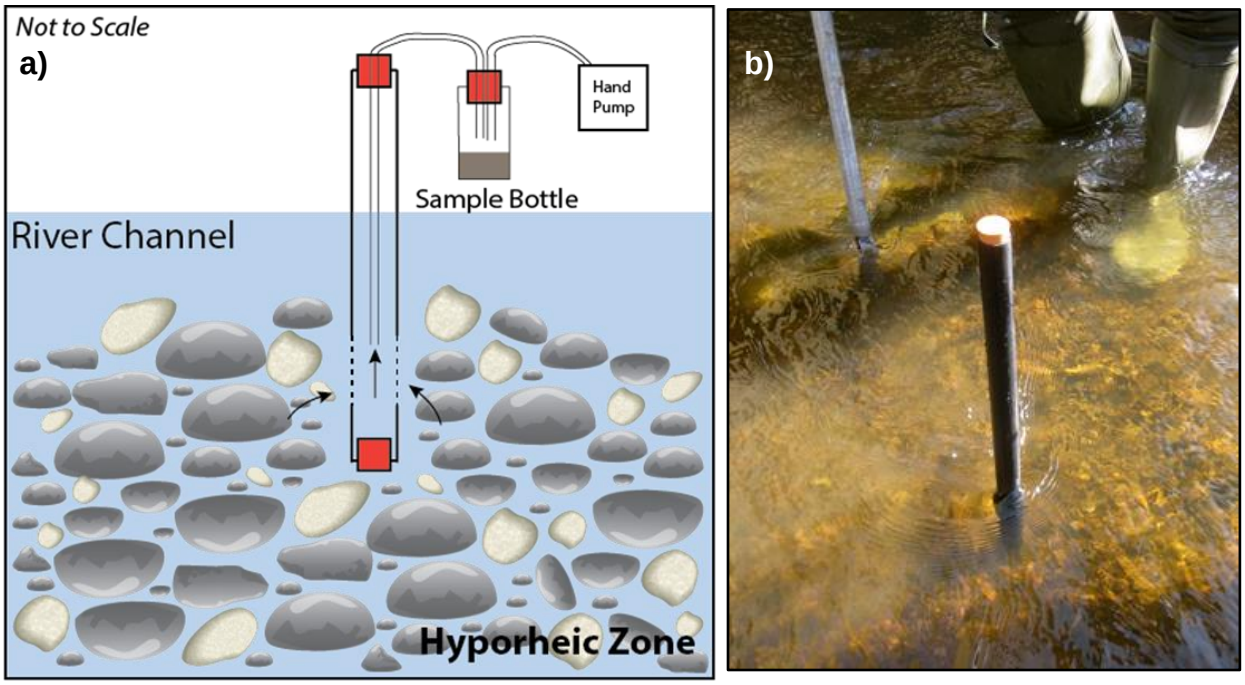

Figure 3: a) Sampling well and pump designed for this study (sediment is not to scale and not of a representative size) b) Sampling well in place on the Risk Esk, North Yorkshire.

Advantages and limitations of pump sampling

Pump sampling is an effective and convenient method. The wells cause minimal disturbance or compaction to the substrate upon insertion, and can therefore be used immediately (Wood *et al*., 2010). They can then be sampled from at regular intervals, over long time periods (Fraser and Williams, 1997; Wood *et al*., 2010). Pump samplers are also affordable, with minimal labour required to construct or use them (Hunt and Stanley, 2000). Another advantage of this method is that perforations in the rigid tubes can be concentrated at particular depths to create multi-level samplers (Riss *et al*., 2008; Rivett *et al*., 2008). These can give a more detailed picture of the changing water quality with distances between groundwater and channel water.

Despite the wide use and advantages of this method, sampling should be approached with care, as there are many factors that may lead to inaccuracy or inconsistency (Palmer, 1993; Scarsbrook and Halliday, 2002). The presence of the wells in the riverbed may have created a new, altered habitat, with different micro-scale flow patterns and substrate characteristics (Palmer, 1993; Hunt and Stanley, 2000). It is also noted that pump sampling is biased towards smaller and less tenacious organisms (Fraser and Williams, 1997), therefore may not give a true representation of the hyporheos.

Advice for pump sampling

- It is important that pH, DO, conductivity, temperature and redox potential are tested immediately after extraction, to reduce inaccuracy with changes in environmental conditions. Riss *et al*. (2008) give a detailed account of a more sophisticated method of *in situ* DO testing, where it is measured within the well itself before extraction.
- To minimise equipment loss, it is important to lodge the wells firmly into the bed. It is also sensible to keep the well height above the HZ as short as is feasible to increase stability.

- Carefully note locations of installed wells, as they may be hard to spot when only just above water level. Black tubes were used in this study to reduce aesthetic impact, but in a more remote location white tubes may be more appropriate.
- This technique could be used to study water quality at different hyporheic depths (Riss *et al*., 2008; Rivett *et al*., 2008), by changing the location of the perforations or the depth of tube beneath the bed. It could also be undertaken at different temporal frequencies.

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