Assessing Hyporheic Exchange: A Review of Methods with Emphasis on Flows and Sediment

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Abstract

Surface water-groundwater interaction in the shallow subsurface along streams can provide various stream functions, including temperature regulation, nutrient cycling, pollutant attenuation, and habitat creation. For these benefits, the hyporheic zone is increasingly considered in river assessments, restoration planning, and engineering design. Scientists and practitioners are interested in identifying and quantifying functions in the hyporheic zone. However, two main complications inhibit efficient and effective hyporheic zone assessment. First, hyporheic zone assessment requires detailed knowledge and experience from a range of scientific disciplines. Second, hyporheic zone functions vary widely in space and time, presenting challenges in scaling results and reaching conclusions.

Hyporheic zone assessments often focus on characterization of hyporheic exchange flows. The hyporheic flow paths, flow rates, and residence times are critical in shaping the presence and magnitude of hyporheic zone functions. The flow rates and residence times are heavily dependent on hydraulic gradients and sediment hydraulic conductivity which can vary greatly in river systems. Sediment hydraulic conductivity is particularly important because it can vary over 8 orders of magnitude in space and time. Also, the type of hyporheic flow informs the available assessment methods, models, and tools. For example, assessment of vertical hyporheic exchange induced by in-stream structures, lateral hyporheic exchange across meander bends, and bank storage during storms could each have different assessment approaches. As a result, hyporheic zone assessment strategies can be complex and vary depending on the focal questions and physical contact of a site.

This technical paper seeks to review methods and techniques to perform a hyporheic zone assessment, with particular focus on hydraulics. Field-based assessment as well as common modeling approaches are included. This paper also includes recommendations for assessing hyporheic zone effects on water quality and ecological communities. Assessments should consider the type of hyporheic exchange, such as in-stream structure-induced exchange, exchange across meanders bends, and bank storage during storms. Secondary goals of this paper are to provide practitioners with an overview of assessment options for their site and to identify knowledge gaps that can be addressed in future research.

Introduction

The hyporheic zone is the region where surface water mixes with groundwater in the shallow subsurface of rivers (Triska et al. 1989). Surface water tends to be high in dissolved oxygen and nutrients, where groundwater is lower in dissolved oxygen and higher in inorganic solutes (Brunke and Gosner 1997). The interaction of surface water and groundwater can provide important functions including stream temperature regulation, nutrient cycling, pollutant attenuation, and habitat creation (Hester and Gooseff 2010). These ecological outcomes are emphasized by recommendations that hyporheic exchange be included in stream restoration (Boulton 2007; Hester and Gooseff 2010; Hester and Gooseff 2011).

The hyporheic zone is increasingly recognized in river management projects for assessment, planning, and design. However, hyporheic zones are usually only qualitatively described in projects, with infrequent quantification of hyporheic exchange and related ecological functions. There are two main complications of hyporheic zone assessment.

1. Assessment requires a multidisciplinary understanding of underlying conditions and processes. For example, hyporheic flow direction and rates are based in hydrology and hydraulics. Stream geomorphology is important in determining the presence and frequency of hyporheic exchange. Water quality constituents, sediment type, and microbial populations are important for biogeochemical reactions and pollutant attention. Identifying hyporheic zone organisms requires an understanding of benthic and hyporheic zone species and their habitats.

2. Hyporheic zone functions can vary widely in space and time. For example, hydraulic conductivity of subsurface sediment is a key factor in determining flow rates in the hyporheic zone. The flow rates influence residence times, which in turn, control time-sensitive hyporheic functions, such as denitrification (Zarnetske et al. 2011).

These two considerations contribute to hyporheic zone assessments being extensive and customized to the site to accomplish specific goals. To assist in planning and development of hyporheic zone assessments, this paper provides a review of the common practices and techniques, with a focus on hyporheic hydraulics and sediment.

Assessment of the Hyporheic Zone

Types of Hyporheic Exchange

Hyporheic exchange refers to the mixing of surface water and groundwater within the hyporheic zone. The flow paths and rates of hyporheic exchange directly influence the extent and importance of the hyporheic zone. The assessment approaches described in this paper focus on characterizing hyporheic exchange, which in turn, characterize the hyporheic zone. There are five (5) general mechanisms of hyporheic exchange that can occur along streams, including turbulent diffusion, hydrostatic forces, hydrodynamic forces, sediment turn-over, and transient stream flows (Kaser et al. 2009; Wondzell and Gooseff 2013). Table 1 summarizes the mechanisms of hyporheic exchange along with common examples and considerations for assessment.

Table 1. Summary of mechanisms of hyporheic exchange.

Hyporheic Exchange Mechanisms	Hyporheic Exchange Examples	Assessment Considerations
Turbulent diffusion: transfer of momentum into the shallow subsurface (Nagaoka and Ohgaki 1990; Packman and Bencala 2000)	Momentum transfer from surface water into subsurface in gravel beds (Tonina and Buffington 2009) and at structures/obstructions (Buffington et al. 2002).	Channel hydraulics, channel obstructions, hydraulic conductivity
Hydrostatic forces: elevated stream water surface elevations apply pressure on the bed and banks, creating hydraulic head gradients that drive flow in and out of the hyporheic zone	Vertical flow along riffle-pools (Ibrahim and Steffler 2012; Tonina and Buffington 2009). Lateral flow across meander bends (Boano et al. 2006; Cardenas 2008; Revelli et al. 2008). In-stream structures (Hester et al. 2009; Endreny et al. 2011; Crispell and Endreny 2009; Sawyer et al. 2011; Briggs et al. 2012).	Hydraulic head gradient, hydraulic conductivity, cross-sectional flow area, confining layers
Hydrodynamic forces: geomorphic features create form drag and build velocity heads (Elliott and Brooks 1997a)	Sand beds with dune or ripple bedforms and low-gradient riffle-pool features (Buffington and Tonina 2009; Wondzell and Gooseff 2013).	Bedforms, form drag, building velocity heads, hydraulic head gradient, hydraulic conductivity
Sediment turn-over: sediment deposits and traps water in pore spaces, and later is mobilized, releasing trapped water (Elliott and Brooks 1997b)	Sediment transport in bedload streams; deposition traps water; erosion releases water (Packman and Brooks 2001; Buffington and Tonina 2009).	Channel hydraulics, sediment transport measurement and modeling
Transient stream flows: changes in stream water levels drive temporary storage of water in the bed or banks	Bank storage during storms (Pinder and Sauer 1971). Bank storage during other flood events: snowmelt, hydropeaking.	Hydraulic head gradient, hydraulic conductivity, cross-sectional flow area, confining layers

A Review of Field-Based Assessments of the Hyporheic Zone

There are several approaches for assessments of the hyporheic zone. Selection of an approach often depends on site constraints and the specific goals of an investigation. A review is provided of some of the most common field-based assessment approaches (Harvey and Wagner 2000). Additionally, once a field-based assessment is performed, this collected data can then be used in modeling assessments, which are discussed later.

Reach scale mass balance: This approach involves measuring streamflow at multiple cross-sections within a reach, upstream and downstream of each hyporheic feature. Then, the change in streamflow between consecutive cross-sections represents net groundwater fluxes into or out of the streambed. It is important to note that this approach does not identify the individual inflow and outflow contributions. This shortcoming can be addressed by also performing streamflow measurement with dilution-gaging using a tracer (Harvey and Wagner 2000).

Subsurface monitoring: Groundwater wells can be used to measure hydraulic head and monitor arrival in tracer studies. The hydraulic head and tracer data can be used together to develop detailed maps of hyporheic flow paths as well as identify the extent of the hyporheic zone (Harvey and Bencala 1993; Wondzell and Swanson 1996; Wroblicky et al. 1998).

Darcy's Law: The calculation of groundwater flow with Darcy's Law allows for direct calculation of hyporheic flows along hyporheic features (Harvey and Wagner 2000). The accuracy of Darcy's Law calculations is dependent on the data collected and the scale over which the calculations are being performed. Flows can be calculated as $Q=KiA$, where "Q" is the groundwater flow rate, "K" is the average hydraulic conductivity, "i" is the average hydraulic head gradient, and "A" is the average cross-sectional flow area. It is recommended to divide calculations into stream-tubes to provide higher resolution in hyporheic hydraulics calculations. In particular, the hydraulic conductivity is a key variable because it varies widely in space and time, and often requires sensitivity analysis.

Conservative tracer studies: Tracer studies provide insight on flow paths and mixing within the hyporheic zone. Tracers can either be injected within the stream itself, or at the upstream end of a hyporheic zone. When the tracer is injected into the stream, the goal would be to identify reach-scale transient storage, including hyporheic exchange. A commonly applied approach is to use the One-Dimensional Transport with Inflow and Storage model (OTIS) (Runkel 1998). OTIS can be used to identify the storage-zone exchange coefficient and a storage-zone cross-sectional area parameter for the hyporheic zone. These parameters can be useful in characterizing hyporheic zone size and exchange rates relative to other hyporheic zones. When the tracer is injected at the upstream end of the hyporheic zone, the specific hyporheic flow paths can be characterized and mapped by monitoring groundwater wells (Triska et al. 1989; Menichino et al. 2012).

Geophysical methods: Electrical Resistivity Imaging (ERI) uses direct or low-frequency alternating current to estimate the distribution of electrical resistance in the subsurface. Electrically conductive tracer studies can be used in combination with ERI to identify hyporheic flow paths and the hyporheic zone (Menichino et al. 2012; Ward et al. 2010; Toran et al. 2012; Ward et al. 2012). Ground Penetrating Radar (GPR) is another geophysical mapping technique that sends electromagnetic pulses into the subsurface and monitors reflection of these waves back to the surface. When performed along the streambank or riparian zone, GPR can be used to identify preferential flow paths in the hyporheic zone (Gormally et al. 2011).

Direct measurement: Seepage meters can be used to directly measure flows across the streambed (Jackman et al. 1997; Wroblicky et al. 1998). Seepage meters store a known volume of water, and slowly release that volume based on the local hydraulic gradient and hydraulic conductivity. It is important to note that it can be challenging to perform seepage meter testing within large rivers, as the device needs to be placed along the streambed in areas of interest.

Developing a Field-Based Assessment of the Hyporheic Zone

There is not a universal approach for field-based assessment of the hyporheic zone. Selection of assessment methods depend on the type of hyporheic exchange and on desired goals of the study. In some studies, more than one approach may be necessary. Below is an example of how to assess the hyporheic zone at the reach scale using the Darcy's Law method discussed in the previous section.

Identify reach-scale constraints: Hydraulic head gradients in the floodplain and deep groundwater effect the gaining or losing condition along a reach (Wondzell and Gooseff 2013). In strongly gaining reaches, the hyporheic flow paths will be confined. In strongly losing reaches, some water will not return to the channel. As a result, it is important to determine background head gradients (1) lateral to the stream and (2) vertically at the channel. This can be accomplished by installing monitoring wells in floodplain groundwater, surface water at the channel, and deep groundwater at the channel.

Confining layers of low permeability sediments, such as clay and bedrock limit the extent of the hyporheic zone. Soil cores can be extracted to confirm the presence and depth of confining layers. Soil profiles should be extracted at several locations within the hyporheic zone sediments to characterize changes in subsurface flow area. Large changes in subsurface flow area can force flow into or out of the aquifer.

Quantify hyporheic flows: Hydraulic conductivity is a key variable that controls hyporheic flow rates (Boulton et al. 2010; Findlay 1995; Hester and Doyle 2008; Hester and Cranmer 2012; Valett et al. 1996). The hydraulic conductivity is strongly linked to the sediment texture and can vary over 8 orders of magnitude in space and time along streams (Calver 2001; Genereux et al. 2008; Song et al. 2010). Hydraulic conductivity can be measured in the field with falling or rising head tests. These tests can be performed using water level loggers in monitoring wells. Hydraulic conductivity can be calculated using Hvorslev's method as described in Fetter (Fetter 2001).

Hydraulic head gradient is used to determine groundwater flow direction and rate. To identify groundwater in the vertical direction, monitoring wells can be placed at different depths at the same location. To identify groundwater flow along the stream or valley, monitoring wells can be spaced apart from one another. The hydraulic head gradient is computed from the difference in the observed water surface elevations at the wells. For hydrostatic-driven hyporheic exchange (e.g., channel-spanning weirs), the water surface elevations along the channel can be used as the hydraulic head gradient.

Cross-sectional flow area is usually estimated from the average saturated area along the hyporheic zone. For an in-stream structure, this can be estimated with an average of stream bed area between the upstream and downstream side.

As discussed earlier, hyporheic flows can be calculated by multiplying these inputs together in Darcy's Law.

Develop connections between hyporheic flows and ecological outcomes: A common goal is to link hyporheic flow to ecological outcomes. As a result, it may be necessary to collect data on hyporheic zone functions. For example, data of interest could be residence times, organic carbon, dissolved oxygen, and temperature (Boulton 2007; Doleolivier and Marmonier 1992; Strayer et al. 1997). Using this data, relationships could be drawn between the hyporheic flow and ecological outcomes. For example, as hyporheic flows increase, the overall extent of the hyporheic zone increases and there may be more physical habitat available for macroinvertebrates found in the hyporheic zone.

Develop reach-scale estimates: Several feature-scale analyses could be performed to develop reach-scale estimates about the hyporheic zone. The simplest approach would be to scale the cumulative effects of the measured features up to the reach scale. However, given the sensitivity of hyporheic exchange to controlling variables (e.g., hydraulic conductivity, hydraulic gradient), this should be limited to reaches that are fundamentally similar throughout (e.g., hydrology, channel hydraulics, geology, valley characteristics).

Models Associated with the Hyporheic Zone

A Review of Models for the Hyporheic Zone

Modeling can provide a detailed level of analysis that can be useful in meeting project goals. For example, modeling can be a tool to test the importance of certain parameters as well as scale-up results. With hyporheic zone assessment, it is common for modeling to be performed after field assessment. The data collected during a field-based assessment can be used as input or calibration data in modeling. A list of the common hyporheic zone models is provided along with a brief description of their applicability (Table 2). Detailed model capabilities and limitations are not described in this paper, and it is recommended that model documentation be reviewed prior to application.

Reach-scale hyporheic models aim to describe hyporheic hydraulics and processes at the scale of a single stream reach. A common reach-scale model is the transient storage model. In the transient storage model, the parameters for storage area and the exchange coefficient can be used to estimate the extent and importance of the hyporheic zone. Network-scale hyporheic models describe hyporheic exchange at the scale of multiple connected reaches. This can be particularly important for performing basin-scale analyses of hyporheic exchange.

Decoupled surface water and groundwater models are also another way to model the hyporheic zone. With decoupled models, surface water is modeled separately and used as input for the groundwater calculation or model. These analyses have typically been one-dimensional (1D), and scope is usually limited to individual hyporheic features (Hester et al. 2008) or reaches (Calfe et al. 2022).

Computational Fluid Dynamics (CFD) models can model a variety of types of hyporheic exchange at different scales (Endreny and Lautz 2012; Menichino and Hester 2014; Li et al. 2022; Yuan et al. 2021). CFD models fully couple surface water and groundwater transport equations, and therefore can model multi-directional hyporheic exchange. Additionally, these models can include packages to simulate solute transport and reactions in the hyporheic zone, which could allow for modeling biogeochemical processes (Li et al. 2020) and temperature dynamics (Menichino and Hester 2014). CFD models of hyporheic exchange are computationally intensive, so these models usually are at the scale of individual hyporheic features. Additionally, it is important to note that the majority of CFD software is proprietary and could have licensing costs. One exception is HyporheicFOAM, which is built on top of the open source OpenFOAM CFD software (Li et al. 2020).

Table 2. Summary of available hyporheic exchange models.

Model	Description (Dimension, Applicability, Scale)	Reference
OTIS: One-Dimensional Transport with Inflow and Storage	Solves the advection-dispersion equation for stream channels with inflowing groundwater and exchange with a 1D transient storage zone that includes the hyporheic zone. Transient storage parameters can be estimated using the One-Dimensional Transport with Inflow and Storage model (OTIS). The parameters for storage area and the exchange coefficient can be used to estimate the extent and importance of the hyporheic zone. No direct simulation of surface water or groundwater hydraulics. Reach-scale model.	Runkel (1998)
NEXSS: Networks with EXchange and Subsurface Storage	Surface and groundwater physical model at the river network scale. Includes multi-dimensional and multi-directional exchange.	Velez and Harvey (2014)
SPARROW: Spatially Reference Regressions On Watershed Attributes	Regional scale statistical model of pollutant fate and transport. No direct simulation of surface water or groundwater hydraulics. Network-scale model.	Schwarz et al. (2006), Son et al. (2022)
HEC-RAS paired with MODFLOW	1D HEC-RAS surface water model and separate multidimensional MODFLOW groundwater model. Groundwater model results characterize hyporheic zone. Feature or reach-scale model.	Hester et al. (2008)
HEC-RAS paired with R scripts	1D HEC-RAS surface water model and separate scripts for computed groundwater transport. Feature, reach, or network-scale model.	Calfe et al. (2022)
Flow3D	3D fully coupled surface water and groundwater CFD model, includes reactive transport. Capable of multi-dimensional hyporheic exchange. Recommended for feature-scale modeling.	Endreny and Lautz (2012)
ANSYS CFX	3D fully coupled surface water and groundwater CFD model, includes reactive transport. Capable of multi-dimensional hyporheic exchange. Recommended for feature-scale modeling.	Menichino and Hester (2014)
ANSYS Fluent	3D fully coupled surface water and groundwater CFD model, includes reactive transport. Capable of multi-dimensional hyporheic exchange. Recommended for feature-scale modeling.	Yuan et al. (2021)
HyporheicFOAM	3D fully coupled surface water and groundwater CFD model, includes reactive transport. Recommended for feature-scale modeling.	Li et al. (2020)
PFLOTRAN: parallel subsurface flow and reactive transport code	3D reach-scale subsurface flow and reactive transport model, includes multi-directional hyporheic exchange. No direct modeling of surface water hydraulics. Reach to network scale model.	Hammond et al. (2020), Fang et al. (2020)
ATS: Advanced Terrestrial Simulator	3D reach-scale fully coupled surface and subsurface flow model, includes multi-directional hyporheic exchange. Reach to network scale model.	Coon et al. (2019), Jan et al. (2019)

Considerations for Selection of a Hyporheic Zone Model

Modeling efforts require balancing desired resolution and accuracy with available resources and time. There are several hyporheic zone modeling options available, each having advantages and limitations. Additionally, model selection is often based on the specific goals of the study. Below several questions are presented, which will help guide model selection.

What type of hyporheic exchange and scale needs to be modeled: There are several modeling options available, however not every option is suited to capture every type of hyporheic exchange. For example, turbulent diffusion exchange may be best captured by computational fluid dynamics models since fine-scale hydraulics can be captured at the sediment-water interface. The type of hyporheic exchange to be captured as well as the project goals dictate the modeling scale. For example, turbulent diffusion exchange could be captured by a computational fluid dynamics model at the sediment or feature scale. It would not be efficient to model these fine-scale hydraulics over an entire reach or river network.

What input data is required: The specific goals of the project often dictate data requirements. For example, with hydraulic conductivity, hyporheic flow models larger than the scale of an individual feature should utilize heterogenous data. Furthermore, given the large sensitivity of results to hydraulic conductivity, even feature-scale models could benefit from heterogenous hydraulic conductivity data. However, collecting heterogenous hydraulic conductivity data can be time-consuming and labor-intensive. Applying a homogenous hydraulic conductivity field can be useful to rapidly assess hyporheic zone hydraulics at the feature-scale.

What questions the results should answer: The type of hyporheic exchange needing to be studied inform what output and detail the model should have. For example, 1D numerical modeling with HEC-RAS is often the most practical tool for understanding reach-average channel hydraulics. These 1D results can be paired with separate Darcy's Law calculations to determine hyporheic hydraulics. This type of approach can provide a rapid assessment of hyporheic exchange, providing flow rates and residence times. Alternatively, multi-dimensional models can provide detailed analysis and a wide range of output that can be analyzed and connected to ecological outcomes. However, multi-dimensional models require more detailed site-specific data, have longer run times, and subsequently cost more to develop.

Conclusions

Assessment of hyporheic zones is challenging because it requires multidisciplinary knowledge and hyporheic zone importance will vary widely in space and time. As a result, it can be difficult to perform assessments, scale results, and reach conclusions. This technical paper provides a review of methods and techniques for hyporheic zone assessment, with particular focus on hydraulics and sediment. Field-based techniques as well as common modeling approaches are included. Generally, the assessment approach will depend on the type of hyporheic exchange and the goals of the study. This paper provides a review of hyporheic zone assessment options for those tasked with selection of field-based methods or modeling approaches.

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