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SHORT COMMUNICATION

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A multi-parameter approach to quantify riverbed clogging and vertical hyporheic connectivity

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Abstract

Riverbed clogging is key to assessing vertical connectivity in the hyporheic zone and is often quantified using single-parameter or qualitative approaches. However, clogging is driven by multiple, interacting physical and bio-geochemical parameters, which do not allow for a conclusive assessment of hyporheic connectivity with single-parameter approaches. In addition, existing qualitative assessments lack transparency and repeatability. This study introduces a Multi-Parameter Approach to quantify Clogging and vertical hyporheic connectivity (MultiPAC), which builds on standardized measurements of physical (grain size characteristics, porosity, hydraulic conductivity) and bio-geochemical (interstitial dissolved oxygen) parameters. We apply MultiPAC at three gravel-bed rivers and show how the set of parameters provides a representative appreciation of physical riverbed clogging, thus quantifying vertical hyporheic connectivity. However, more parameters are required to fully characterize biological clogging. In addition, MultiPAC locates clogged layers in the hyporheic zone through multi-parameter vertical profiles over the riverbed depth. The discussion outlines the relevance of MultiPAC to guide field surveys.

KEYWORDS
colmation, dissolved oxygen, grain size, hydraulic conductivity, porosity, siltation

1 | INTRODUCTION

Vertical connectivity is a fundamental attribute of functional river ecosystems. Dynamic exchange processes between fluvial and groundwater systems represent a vital ecohydraulic link, which is possible in the presence of a permeable hyporheic zone (Boulton et al., 1998; Orghidan, 1959). The porous nature of the hyporheic zone is an important factor for fish spawning (e.g., Boulton, 2007; Heywood & Walling, 2007), groundwater recharge (e.g., Brunke & Gonser, 1997), and it represents a habitat for macroinvertebrates (e.g., Strommer & Smock, 1989). Fine sediment infiltration leads to the physical clogging of hyporheic interstices (Battin & Sengschmitt, 1999) and a reduction in pore space and hydraulic conductivity in the riverbed (Schälchli, 1992). Riverbed clogging impairs the water exchange between the surface and groundwater, which means that less oxygen-rich water from the surface is available in the hyporheic zone (Brunke & Gonser, 1997). Thus, clogging decreases or even interrupts the supply of interstitial dissolved oxygen (*IDO*) to incubating fish eggs (Kemp et al., 2011), and other aquatic species of the hyporheic ecotone, such as benthic organisms (Boulton et al., 1998). While clogging and declogging cycles occur in natural systems in response to hydrological conditions (Blaschke et al., 2003), anthropogenic-influenced rivers often experience monotonous flow dynamics and increased fine sediment loads (Walling & Fang, 2003), thus leading to accelerated infiltration and accumulation of fine sediment in the riverbed (Brunke, 1999). In consequence, alterations to the natural integrity of the hyporheic zone result in disrupted vertical hyporheic connectivity.

The assessment of riverbed clogging is key to evaluate hyporheic rehabilitation actions (Boulton, 2007). Yet, existing approaches for assessing riverbed clogging rely either on single, particular parameters (e.g., Blaschke et al., 2003; Datry et al., 2015), empirical equations to infer multiple parameters (e.g., Descloux et al., 2010), or qualitative descriptions of the substrate conditions (e.g., Schaelchli et al., 2002). Thus, to the authors' best knowledge, the need for methods to objectively measure clogging processes, and therefore, vertical hyporheic connectivity remains. Commonly-used physical parameters for characterizing riverbed clogging are (Seitz, 2020):

a. *Grain size characteristics* of the riverbed provide information on the sediment composition (e.g., characteristic grain size, sorting coefficient), in particular, fine sediment fractions (*FSF*) for the assessment of fine sediment infiltration (e.g., Descloux et al., 2010; Schälchli, 1992).
b. *Porosity* (i.e., the ratio of pore volume to the total volume of a sample, n) provides an estimation of the available pore space in the riverbed (e.g., Maridet & Philippe, 1995) and is a key parameter driving the clogging depth (Huston & Fox, 2015).
c. *Hydraulic conductivity* (k_f) describes the ease with which water moves through a saturated porous medium (Freeze & Cherry, 1979), thus reflecting a reduction in interstitial pore space in clogged riverbeds (e.g., Datry et al., 2015).

The separate consideration of the three above-listed parameters in the referenced studies has limitations for parametrizing hyporheic status. For instance, high porosity can result from a uniform grain size distribution, which leads to high pore volume but insufficient pore sizes for a suitable habitat. The limitation of using only the porosity as a hyporheic indicator becomes evident by examining sandy riverbeds, which can have a porosity of up to 0.45, but the pore spaces are too small to serve as habitat for juvenile gravel-spawning fish (Kemp et al., 2011; Seitz, 2020). In addition, grain size characteristics, in particular *FSF*, vary with rivers, river reaches, and morphological units within a river reach (Datry et al., 2015). Thus, a universal *FSF* threshold for clogging, and consequently for vertical hyporheic connectivity, is not representative.

Another often-considered key parameter to assess vertical connectivity and riverbed clogging is hydraulic conductivity k_f (Blaschke et al., 2003; Datry et al., 2015; Descloux et al., 2010; Newcomer et al., 2016). However, missing reference values from near-census natural riverbed conditions make assessments with only hydraulic conductivity hardly applicable. Qualitative methods, such as mapping of surface clogging, are subjective and involve a high observer bias. They are also rarely repeatable, transferable, nor suitable to assess the hyporheic zone in the subsurface (Brunke, 1999; Descloux et al., 2010). Moreover, bio-geochemical processes in the hyporheic zone (e.g., microbial growth) and to-date unknown interactions between bio-geochemical and physical factors make the identification of clogging with single-parameter approaches incomplete or non-meaningful. For instance, in the absence of sufficient *IDO*, oxygen-dependent processes such as respiration and nitrification decrease, but anoxic processes still continue and lead to intensified microbial growth (Wharton et al., 2017). The resulting microbial colonization and biofilm growth clog sediment interstices, which is also referred to as biological clogging (Battin & Sengschmitt, 1999; Brunke, 1999; Descloux et al., 2010; Hoffmann & Gunkel, 2011). A review of reference values of *FSF*, n, k_f, and *IDO* from previous studies is provided in Tables S1–S4 in the Supplementary Material.

In view of the ecohydraulic importance of *IDO* and its significance for biological clogging, we consider the integral combination of parameters the baseline for characterizing riverbed clogging and vertical hyporheic connectivity. Thus, we seek to answer if the above-mentioned set of parameters is relevant for quantifying riverbed clogging and vertical hyporheic connectivity. To answer the research question, this study introduces a novel Multi-Parameter Approach to quantify Clogging and vertical hyporheic connectivity (MultiPAC). Notably, MultiPAC involves the following: (a) freeze cores for subsurface sediment characteristics, (b) a photogrammetric approach for measuring porosity n (Seitz et al., 2018), (c) so-called VertiCO method for measuring hydraulic conductivity k_f and *IDO* over the riverbed depth (Aybar Galdos et al., 2023; Seitz et al., 2018). We hypothesize that MultiPAC provides a representative appreciation of clogging effects and vertical connectivity within the hyporheic zone. To test the hypothesis, we apply MultiPAC at three gravel-bed rivers in Germany with different morphological and sedimentological characteristics.

2 | MATERIALS AND METHODS

2.1 | Study sites

This study used three study sites in Southern Germany, the Eyach, Glatt, and Inn River, which have an average discharge of 3.2, 4.1, and 106.0 m^3/s, respectively. The field surveys were conducted between 2018 and 2020. The Eyach and Glatt Rivers are tributaries of the Neckar River, which drains into the Rhine River. The river reaches at the Eyach (48°22′52.3″ N, 8°47′30.2″ E) and Glatt (48°23′41.22″ N, 008°38′40.75″ E) River were characterized by clean, loose gravel beds in fast flowing waters. Dense riparian vegetation and engineered river banks prevented bank erosion at these two rivers' reach.

The study site at the Inn River (48°14′35.64″ N, 12°34′51.49″ E) was located at the end of a 31.2 km-long residual river reach between a diversion weir and a hydropower plant, upstream of the river's confluence with the Danube River. This river reach was characterized by a regulated flow throughout the year and high snowmelt-driven suspended sediment loads. The study site was situated on a morphodynamically inactive gravel bar with a high amount of fine sediment covering surficial sediments and apparent biofilm growth (cf. Figure S2 in the Supplementary Material). The site was located approximately 500 m downstream of a river ramp, where low turbulences and flow velocities were present.

Figure S1 in the Supplementary Material shows in detail the location of the MultiPAC measurement points. The number of MultiPAC measurements per study site was determined as funding permitted. Each measuring technique (freeze core and VertiCO) was performed at every study site at two neighboring, longitudinally-distributed locations with a 1- to 2-m-distance between the first and duplicate (repetition) measurement.

2.2 | Measuring techniques

2.2.1 | Grain sizes and porosity with freeze core samples

The freeze core technique yields sediment samples of the subsurface while preserving the primary riverbed structure and fine sediment fraction *FSF* (Carling & Reader, 1981). The freeze core methodology applied in this study involved hammering a standpipe into the submerged riverbed and injecting liquid nitrogen to freeze the surrounding saturated substrate. The methodological details of the applied procedure can be found in Seitz et al. (2018). Freeze core samples with lengths between 0.5 and 0.7 m and diameters between 0.2 and 0.3 m were pulled from the riverbed with a tripod and visually inspected to identify possible sediment stratifications. Next, a set of approximately 250 overlapping photographs of each freeze core sample was taken in-situ from five different camera angles. Structure-from-Motion with Multi-View Stereo (SfM-MVS) was used to post-process the photographs with Agisoft Metashape (Agisoft, 2022) into a three-dimensional (3D) model of the sample (Seitz et al., 2018), which yielded the total sample volume V_{tot}. Afterward, the freeze core sample was thawed, dried (at 105°C for 24 h), and dry-sieved in the laboratory to determine the grain size fractions (Wentworth, 1922). A subsequent water replacement method was performed to determine the pure sediment volume V_{Se}. The sieving process provided grain sizes to derive *FSF* with two differentiators, namely $FSF < 2$ mm and $FSF < 1$ mm. We used grain size characteristics in millimeters to evaluate the sorting coefficient $SO = \sqrt{\frac{d_{84}}{d_{16}}}$ (Bunte & Abt, 2001) and thus distinguish poorly sorted sediment with small pore spaces. It should be noted that the removal of organic matter from the freeze core samples prior to sieving was not conducted. Thus, the *FSF* results in the following do not differentiate between organic and mineral sediments.

Due to the volumetric expansion effect of the water from the liquid to the frozen state, which is approximately 9.17% (Kell, 1975), the total sample volume determined with SfM-MVS needed to be corrected accordingly. Thus, 9.17% of the sample pore volume ($V_{tot} - V_{Se}$) was subtracted from the total sample volume to account for the water expansion within the freeze-core samples (Seitz, 2020). The ratio between pore volume and total sample volume (corrected from water expansion) resulted in the bulk sample porosity *n*:

$$n = 1 - \frac{V_{Se}}{V_{tot} - 0.0917(V_{tot} - V_{Se})} \tag{1}$$

A disadvantage of the freeze core technique in gravel-bed rivers is that sample representativeness is not ensured due to large cobbles. Thus, we removed large grain sizes from both grain size and porosity analysis according to Seitz et al. (2018) to fulfill the 5% criterion of Church et al. (1987), which ensures a sampling accuracy of 95%. Notably, grain size fractions coarser than 125 mm were excluded from both Eyach and Glatt River samples and fractions coarser than 64 mm from the Inn River samples.

2.2.2 | Interstitial dissolved oxygen and hydraulic conductivity with VertiCO

The VertiCO (Vertical profiles of hydraulic Conductivity and dissolved Oxygen) technique (Seitz, 2020; Aybar Galdos et al., 2023) serves to measure *IDO* and k_f with high vertical resolution (i.e., over the riverbed depth). Figure 1 illustrates the experimental setups used for measuring *IDO* and k_f. Longitudinally distributed perforations with a diameter of 10.5 mm along a standpipe enabled to measure both *IDO* and k_f at 15 vertical positions. The standpipe was hammered into the submerged riverbed to a depth of 0.45 to 0.5 m and a so-called double packer (DP) was positioned inside the standpipe for measuring the parameters at the 15 perforation depths. The DP had two rubber segments to vary measuring positions while ensuring no interference of water coming from lower or higher depths. For *IDO* measurements, a measuring chamber with an optode (HACH HQ30d) was connected to the DP. A three-valve syringe ensured that sufficient water (50 to 150 10^{-3}L) was sucked into the measuring chamber. The *IDO* measuring setup was afterward replaced with a so-called slurping setup for measuring slurping rates (i.e., the rate of water flowing into the DP through a perforation because of suction created with a vacuum pump). The slurping setup consisted of two hoses connecting a flask with the DP and a vacuum pump. As the suction pressure built up inside the flask, water started to flow into the flask until a steady state was reached. The increasing water weight was recorded at every measuring position for 1.5 minutes to determine slurping rates.

Because slurping rates are influenced by the hydraulic head, a transformation to hydraulic conductivity k_f was necessary. Correlation curves between slurping rate and hydraulic conductivity (e.g., Terhune, 1958) are not appropriate since the influences of the water level and sediment depth are highly dependent on sediment characteristics. This is why we used a calibrated MODFLOW-2005 (Harbaugh, 2005) model to convert slurping rates to k_f, which takes as input both hydraulic and sedimentological parameters (grain size and porosity). Freeze core samples taken in the vicinity of a slurping point provided the sedimentological boundaries for the MODFLOW model. The codes for running the model are freely available (Seitz et al., 2022). For the analysis, we plot *IDO* saturation (*IDOS*) (in %), which was calculated as the ratio between the actual dissolved oxygen concentration and the maximum concentration that can be dissolved at a given temperature in static conditions. Thus, *IDOS* can be higher than 100% because of water aeration stemming from natural turbulent conditions and accounts for temperature and atmospheric pressure at the time of the measurement, which improves comparability across study sites. *IDO* values are also reported in concentration (mg/L) in the results.

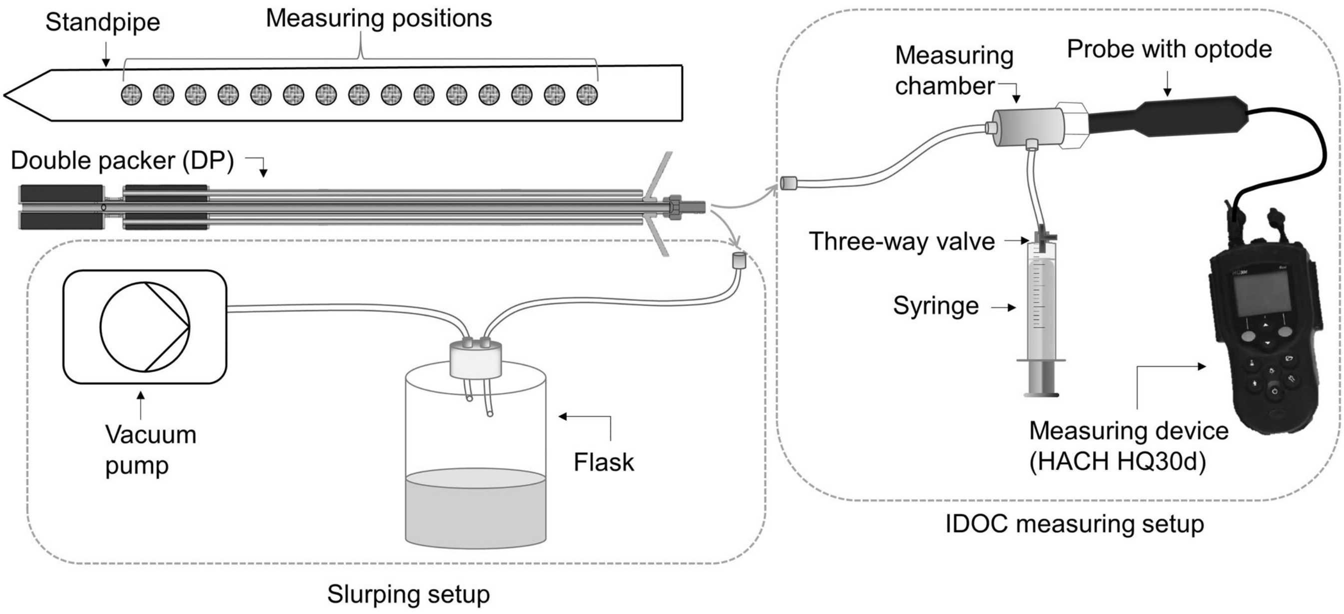

FIGURE 1 *IDO* and slurping measuring setups of the VertiCO method.

TABLE 1 Grain size characteristics and porosity *n* of the freeze core samples at the three study sites.

Site	Water depth [m]	Sample weight[a] [kg]	d_{50} [mm]	*SO* [−]	*FSF* [%] < 2 mm	*FSF* [%] < 1 mm	*n* [−]
Eyach 1	0.25	9.845	15.2	4.4	14.0	8.1	0.29
Eyach 2	0.22	14.705	19.0	3.6	18.6	12.7	0.26
Glatt 1	0.31	10.915	10.6	8.4	27.6	24.0	0.31
Glatt 2	0.37	11.980	22.8	4.3	14.2	12.3	0.19
Inn 1	0.22	23.465	37.9	5.2	12.8	10.1	-
Inn 2	0.26	23.200	33.0	6.0	14.1	11.3	0.11

[a] Final sample weight after adaptation to 5% criterion of Church et al. (1987).

3 | RESULTS

3.1 | Overview of freeze core and VertiCO measurements

Table 1 shows the freeze core measurements in the form of d_{50}, *SO*, *FSF*, and *n*. In addition, Figure S3 in the Supplementary Material shows the freeze core samples from the three study sites. Figure 2 plots the VertiCO measurements of k_f and *IDOS* at the study sites. The measurements were marked with 1 and 2, indicating the first and second (duplicate) measurements, respectively. While the grain sizes, *FSF*, and porosity provide bulk riverbed information, *IDO* and k_f were measured as vertical profiles with a high resolution over the riverbed depth.

The d_{50} values in Table 1 indicate that the Inn River had a coarser sediment composition than the Eyach and Glatt River. Thus, the freeze cores samples had to be approximately 2 times larger. The next sections report these measurements in light of the geomorphic environments of the three study sites.

3.2 | The Inn River

Despite the coarse grain sizes (Table 1), a low porosity of $n = 0.11$ was observed at the Inn River from the SfM-MVS analysis, which indicates small pore space. In general, low porosity can be a result of fine sediments filling interstitial space. Still, the *FSFs* were only moderate (*FSF* < 2 mm between 12.8% and 14.1%) and do not explain the low porosities. Descloux et al. (2010) measured fine sediment fractions (< 2 mm) between 8.3 and 55.2% ranging from lightly to heavily clogged sediments with the freeze core technique. However, from an ecological point of view, an impact on the reproduction of gravel-spawning fish can be already expected for *FSF* < 1 mm of 8% and *FSF* < 2 mm of 9% (Heywood & Walling, 2007).

The high sorting coefficients *SO* (5.2–6.0) suggest poorly sorted sediment with limited pore space (Bunte & Abt, 2001), and therefore, correspond well to the measured porosities. A limitation associated with the non-representative sampling of freeze cores in gravel-bed rivers is that *FSF* is often biased toward low values as a consequence of occasional boulders (Descloux et al., 2010; Milan et al., 1999). This

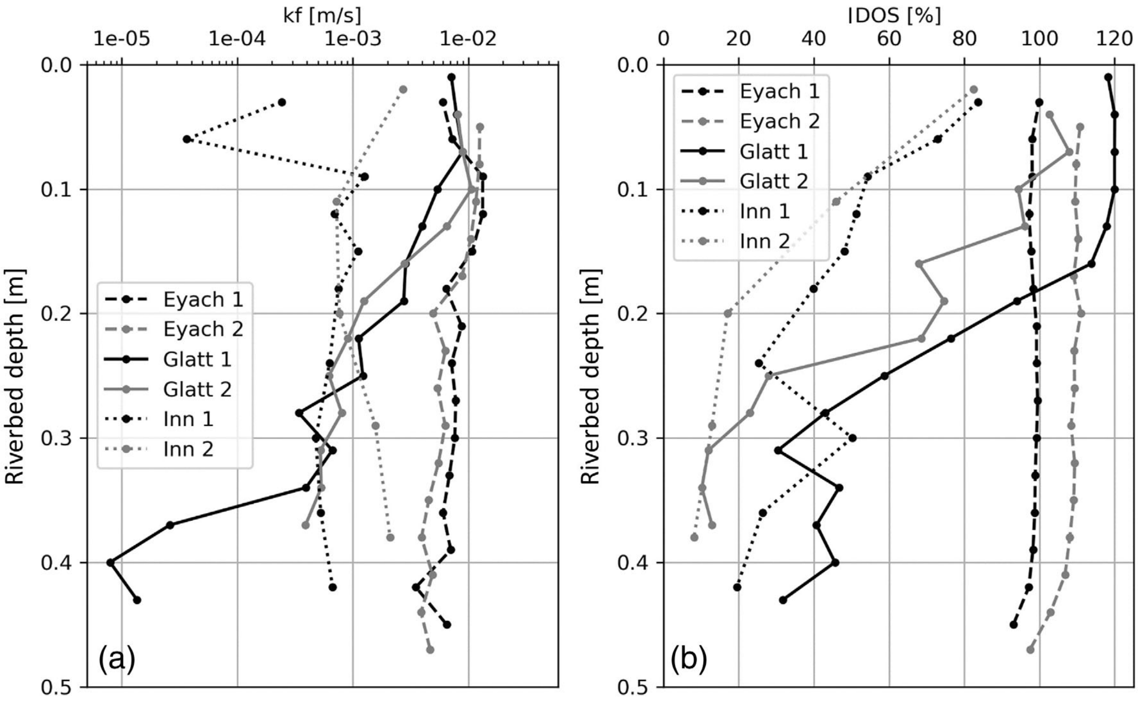

FIGURE 2 Vertical profiles of hydraulic conductivity k_f and interstitial dissolved oxygen saturation *IDOS* over the riverbed depth for the Eyach, Glatt, and Inn sites.

was also observed in the freeze core samples of the Inn River. However, this bias can be disregarded here because large grain sizes (> 64 mm) were dismissed from the analyses by removing the volume of the large grains from both pure sediment volume (V_{Se}) and total sample volume (V_{tot}).

The hydraulic conductivity k_f measured at the Inn River correlated well with the low porosities (Figure 2a). Large deviations in k_f between the first and duplicate measurements were observed in near-bed (< 0.1 m) and deep (< 0.3 m) subsurface layers, where k_f values of the duplicate measurement differed up to a factor of approximately 30 from the first measurements. Still, k_f remained low (between 3.7e−05 and 2.7e−03 m/s) over the entire riverbed depth, which is problematic from an ecological point of view. For instance, Rubin (1998) reported no egg-to-fry survival for k_f values below 5.6e−3 m/s. Heywood and Walling (2007) emphasized the role of high *IDO* during the incubation of salmonid eggs in the hyporheic habitat and showed that concentrations between 4 and 5 mg/L can be associated with 76% to 100% of salmonid embryo mortality. *IDO* may be influenced by several mechanisms, such as upwelling/downwelling effects, clogging, and biological oxygen consumption. Given the apparent biofilm growth on surficial sediments at the Inn River, the low *IDOS* values < 51.2% (concentration of 4.6 mg/L) at depths > 0.1 m may be a result of ongoing anoxic processes associated with microbial growth (cf. Figure 2b). In addition, previous studies linked a reduction in hydraulic conductivity to biomass clogging pore spaces in the hyporheic zone (Ulrich et al., 2015). Thullner et al. (2002) conducted numerical simulations of clogging through biofilm growth in different grain sizes and sorting coefficients. Their results show the strongest clogging in poorly sorted sediment, with a decrease in hydraulic conductivity of a factor up to 100. These findings correspond to the poorly sorted sediments and very low *IDO* at the Inn River.

3.3 | The Eyach and Glatt River

The Eyach and Glatt River showed higher porosity ($n > 0.19$) compared to the Inn River (Table 1), which generally indicated larger pore volumes. The Eyach River presented low *FSFs*, similar to the Inn River, while the *FSFs* at the Glatt River showed partly higher values (*FSF* < 2 mm of 27.6% at Glatt 1). Taking only into account the high porosity at the Glatt River would lead to the conclusion of higher available pore space, and thus, higher vertical hyporheic connectivity at the Glatt River site than at the Eyach River site. However, given the high *FSF* (Glatt 1), the high porosity (Glatt 1) could be a result of an expansion effect due to cohesive fine sediments. For instance, silt and clay fractions can cause a rapid increase in overall porosity due to higher water retention (Carling & Reader, 1982).

The duplicate measurements at the Glatt site (i.e., Glatt 2) deviated considerably compared with the Glatt 1 measurements. The *FSF* values at Glatt 2 (e.g., *FSF* < 2 mm of 14.2%) were approximately half of the values of Glatt 1 and the measured porosity is lower ($n = 0.19$). These results suggest a high natural spatial variability within the study site at the Glatt River and confirm that Glatt 2 had locally better interstitial connectivity. Both k_f and *IDOS* measurements at the Glatt River had a sharp decrease over the depth (Figure 2). The depth gradients of k_f and *IDOS* indicate a reduction of water exchange between the surficial and deeper areas of the hyporheic zone, and thus, align with the *FSF* and porosity observations at Glatt 1. Substantial physical clogging becomes evident at depths > 0.3 m, where *IDOS* and k_f values reach up to 10.2% (0.96 mg/L) and 7.9e−6 m/s, respectively. From these depth gradients, the development of a clogging layer between sediment depths of 0.1 and 0.3 m can be observed. However, due to the large deviation observed in the sedimentological parameters (d_{50}, *FSF*, *n*) at the Glatt River, fluctuations in the vertical location of clogging in the river reach can not be excluded.

In contrast to the Glatt River, the hydraulic conductivity and *IDOS* profiles at the Eyach River remained high and nearly constant over the depth, which indicates dynamic hyporheic exchange, and thus, high vertical connectivity within the hyporheic zone. The high k_f (3.5e−3 to 1.3e−2 m/s) and *IDOS* (93.1 to 111%) values at the Eyach River, along with the high porosities (0.26 to 0.29) and low *FSF* (e.g., *FSF* < 0.5 mm between 2.9% and 7.4%), indicate no riverbed clogging.

4 | DISCUSSION

4.1 | Relevance of MultiPAC

Previous studies attempted to use hydraulic conductivity k_f to characterize clogging and confirmed k_f as key indicator (Blaschke et al., 2003; Datry et al., 2015; Descloux et al., 2010). However, the reported k_f threshold values for indicating riverbed clogging differ significantly. While Blaschke et al. (2003) state k_f threshold values between 1e−7 and 5e−7 m/s, Datry et al. (2015) report values between 2e−5 and 5.5e−5 m/s. Thus, the k_f values of approximately 1e−3 m/s at the Inn River would not correspond to clogging conditions. However, our observations suggest an impairment of exchange within the hyporheic zone, which may be associated with biological clogging. To gain more insight on the presence of biological clogging in future studies, we recommend the acquisition of biomass data (e.g., Battin & Sengschmitt, 1999).

A clogged riverbed is characterized by reduced pore space and Maridet and Philippe (1995) found a threshold for clogging based on porosities smaller than 0.06. According to this threshold, regarding porosity *n* only, the Glatt River would have no clogging (*n* > 0.19). However, the *FSF* results suggested that the high porosity is possibly a result of high cohesive sediment fractions. The k_f and *IDOS* vertical profiles, which steeply decrease over the riverbed depth, indicated the development of a clogged layer, and thus, a disrupted vertical connectivity within the hyporheic zone.

The vertical profiles of *IDOS* aid in analyzing oxygen consumption by microbial activity in the hyporheic zone at the Inn River where biofilm growth was apparent. At the Eyach River, the *IDOS* profiles indicated good exchange conditions in the hyporheic zone, and thus, confirmed the observation of no apparent riverbed clogging. In addition, the steep *IDOS* gradients over the riverbed depth measured at the Glatt River correlated well with the hydraulic conductivity and supported the interpretation of a clogged layer at approximately 0.1 to 0.3 m riverbed depth. However, the *IDOS* profiles have limitations when not used in combination with other parameters, which precludes them from being used as a single-parameter characterizing riverbed clogging. For instance, exfiltrating oxygen-poor groundwater (i.e., upwelling) may lead to a low measured *IDOS*, which is unrelated to clogging effects or loss of vertical connectivity.

Thus, compared with single-parameter approaches, the combination of physical riverbed and the bio-geochemical *IDO* parameters in MultiPAC are more suitable to quantify clogging, which represents evidence for our hypothesis that MultiPAC provides a representative appreciation of clogging effects and vertical connectivity within the hyporheic zone. However, future research is required to fully describe complex biological clogging processes.

4.2 | Uncertainty and challenges

A limitation of MultiPAC is that the high spatiotemporal variability of clogging processes combined with potentially scarce measurement points may result in high epistemic uncertainties in the measurements. By means of duplicate measurements, we aimed to quantify the natural spatial variability of the measured parameters, and thus, epistemic uncertainty. However, expert interpretation was required when large deviations were measured in the duplicate measurements, such as at the Glatt River, and thus, subjective bias may have been introduced. For this reason, five MultiPAC points can be performed per site in line with previous studies investigating gravel-beds with the freeze core technique (e.g., Thoms, 1992). In addition, a minimum distance of 0.5 m between measurements is required to avoid measurement interference (Seitz, 2020). Future research will also need to refine in-situ interpretations of clogging by providing confidence intervals for the MultiPAC measurements.

In contrast to *IDO* and k_f, the porosity *n* and grain size characteristics are not explicitly measured over the riverbed depth but depth-integrated from freeze core samples. Although freeze core samples were visually inspected in-situ, a quantification of vertical grain size characteristic variations is not possible with the described methods. As a result, the MODFLOW model for computing the hydraulic conductivity considers a homogeneous riverbed. Approaches for splitting freeze core samples into individual sub-samples, which can represent several depth intervals (e.g., Milan, 1996), represent a possibility to adjust the modeling hypothesis for determining k_f. However, the ratio between the gravel size and weight of the sub-sample can cause an over-representation of large grains. Thus, coarse grain size fractions would need to be excluded from the grain size analyses to ensure the representativeness of every freeze core sub-sample.

5 | CONCLUSIONS

Riverbed clogging is a function of multiple physical and bio-geochemical factors and affects ecohydraulic connectivity in the hyporheic zone. Methods for assessing the riverbed with single parameters are not suitable to quantify the physical or biological clogging state. This study introduces the novel multi-parameter MultiPAC method to identify clogging and assess vertical hyporheic connectivity. MultiPAC overcomes single-parameter approaches due to the integrated analysis of key parameters. For instance, a strong decrease in hydraulic conductivity and interstitial dissolved oxygen content over the riverbed depth associated with high fine sediment fractions indicates physical clogging at one of the study sites, even though high porosity was measured. The high vertical resolution of MultiPAC allows the identification of clogging, while river reaches can be spatially investigated with multiple MultiPAC points. Although the grain size characteristics in conjunction with hydraulic conductivity could be a solution to clogging identification, dissolved oxygen measurements aid in describing hyporheic exchange conditions and biological clogging. Future challenges involve performing depth-explicit grain size analysis of the freeze core samples and the parametrization of biological clogging.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

The codes created for this study are available on Github (https://github.com/Ecohydraulics/kf-converter-w-flopy).

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