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Improved geohydraulic characterization of river bed sediments based on freeze-core sampling – Development and evaluation of a new measurement approach

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Prior to hydraulic engineering work, it is essential to know the geohydraulic properties of river bed sediments as precisely as possible in order to predict and minimize potential effects on adjacent aquifers. Many different methods are available, but all have limitations. Some destroy the natural sediment structure, others lack a small-scale resolution, and all fail to determine anisotropy. In this study, we present a new measuring approach to determine hydraulic conductivity (K) and anisotropy at a detailed scale. Frozen, undisturbed sediment samples taken with the freeze-core technique form the basis of our approach. Orientated core cutter samples are taken from the freeze-cores at different depths and examined by means of falling-head lab permeameter tests, in order to obtain detailed profiles of vertical and horizontal K values and anisotropy. The approach was tested with natural sediment samples from the bed of a channel near Potsdam, Germany, and with samples from an experimental container. For comparison and evaluation, hydraulic conductivities were also determined by means of in situ permeameter tests and empirically, on the basis of grain-size distribution (GSD). The results show a large discrepancy between the empirically determined hydraulic conductivities and the directly measured hydraulic conductivity with lab and in situ permeameter tests. We conclude that empirical methods based on GSD are not suitable for determining in situ conductivity of river bed sediments. Our new approach enables an improved geohydraulic characterization of river bed sediments including the determination of anisotropy.

Keywords: Clogging, River bed, Hydraulic conductivity, Anisotropy, Permeameter test, Freeze-core

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1 Introduction

The hydraulic interaction of surface water and groundwater is of great importance regarding the resource management of water works using river bank filtration. Furthermore, detailed knowledge of the interaction process is necessary to assess the effects of hydraulic engineering on adjoining aquifers. Therefore, the structure and the geohydraulic properties of the river bed must be known as precisely as possible with regard to its role as a filter medium and its effect on water quality. River bed sediments often act as a filter which retains fine particles of the infiltrate. This causes shrinkage of pore volume and subsequently a consolidation of the filter layer alongside a reduction of hydraulic conductivity and possibly a development of a pronounced anisotropy (Schälchli, 1993). In this context, the hydraulic conductivity and the anisotropy of river bed sediments affect the hyporheic exchange (Salehin et al., 2004) and can be viewed as key variables of this process. There are a variety of methods to estimate the hydraulic properties of river bed sediments on different scales (cf. Kalbus et al., 2006; Rosenberry and LaBaugh, 2008). Hazen (1893) formulated an empiric way to estimate the hydraulic conductivity K_g of sediments based on their grain-size distribution. For geotechnical and hydrogeological questions, this has become a standard method and can also be applied to river bed sediments. His approach has since been further developed by numerous authors to expand the applicability to different sediment compositions (e.g. Beyer, 1964; Köhler, 1965; Wittmann, 1981), but all methods have restricted application domains. With regard to K value determination, Tavenas and Ladd (1973) conducted a comparative testing program with 41 soil laboratories and came to the conclusion that the gradation test results show a large variability and low reproducibility between individual laboratories. They detected a difference of 20% for estimating d_{10}

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using identical sample material. Matthes et al. (2012) also observed considerable discrepancies in a cooperative program. The determined values for d_{10} of samples consisting mainly of sand varied by 112% amongst the individual testers. The difference was even more significant for silty, clayey specimens, the d_{50} difference being 203%. Especially precise grain-size distributions measured with sieve analysis of samples with a high percentage of fine fractions are more prone to error, as demonstrated by Matthes et al. (2012). The application boundaries of many methods, however, do not exclude such sediment compositions (cf. Hazen, 1893; Beyer, 1964). Uncertainties, which arise by determining the grain-size distribution also influence empirical methods applied to determine the hydraulic conductivity of sediment. This error propagation results in major inaccuracies. Furthermore, Matthes et al. (2012) found that the measurement uncertainty of gradation analysis increased the deviation error of calculated K_g values by several orders of magnitude. In addition, the original sediment structure is destroyed by sieving along with any disrupting mechanisms responsible for an increased hydraulic resistance. Cheng et al. (2013) investigated the influence of (oriented) stratification on the hydraulic properties of sediments. They noted that cross-bedding or other sediment compositions resulted in a significant difference in hydraulic conductivity for varying orientations even if the sediment was well-sorted. Biofilms can lead to a reduction of the hydraulic conductivity of river bed sediments, too (Nevo and Mitchell, 1967; Rinck-Pfeiffer, 2000). Due to the methodological approach by determining the grain-size distribution, the natural structure of the sediment and its natural bulk density is changed. Thus, no information of its initial conductivity in the original structure or the anisotropy can be obtained (Song et al., 2009). In situ permeameter tests, in contrast, enable the determination of the vertical conductivity K_v of river bed sediment in its original sediment structure (Landon et al., 2001). Song et al. (2009) drew a comparison between in situ permeameter tests and empirically calculated conductivities based on grain-size distribution. Their study showed a systematic variance between the different approaches. The calculated hydraulic conductivities based on empirical methods are considerably higher compared to the values of K_v determined from in situ permeameter tests. Landon et al. (2001) outline other in situ methods to determine the conductivity on a small and medium scale. The horizontal conductivity K_h of river beds can be estimated, for example, with slug and bail tests (Springer et al., 1999). The in situ vertical conductivity K_v can be ascertained if the exchange flow measured with a seepage meter is combined with the determined hydraulic potential distribution in the river bed (Fleckenstein et al., 2006). Only few methods allow the determination of the hydraulic anisotropy of river bed sediments. Systematic errors caused by scale-effects occur if different methods to quantify the vertical and horizontal hydraulic conductivity are combined regardless of their scale dependent application limits. Chen (2000) used in situ permeameter tests to detect the anisotropy of the river bed by adding bent infiltration pipes accompanying the usual infiltration pipes, to measure the horizontal conductivity K_h of the river bed. However, due to the experimental set-up, Chen's (2000) method to determine K_h is restricted to only one specific depth per measuring point. Also, a simultaneous measurement of K_v and K_h is only possible within a range of minor spatial displacement. Yet, in most cases the hydraulic properties of river beds are subject to pronounced spatial heterogeneity (Chapuis, 2012), which would cause further uncertainties, if the method were applied. In another measuring campaign he used the direct-push technology to gain additional depth-oriented information (Chen et al., 2008). This, however, also does not determine the anisotropy directly. Our study shows a possible way to determine the in situ conductivity and anisotropy of river bed sediments on a small scale, which counteracts and minimizes the negative influence of observational errors and scale effects. The presented approach offers the possibility to determine the hydraulic conductivity of river bed sediments in vertically and horizontally orientated high-resolution. It is built on a series of consecutive experimental steps (Fig. 1) which conclude in a comprehensive understanding of the river bed and its geohydraulic properties. The introduced procedure starts with freeze-core sampling of the river bed (I). The freeze-core sampling technique allows undisturbed sampling of cohesionless sediments by freezing the sediment whilst preserving its original sediment structure. Undisturbed sediment samples can be taken up to a soil depth of 1.5 m. Freeze-core sampling of the river bed can be performed from a boat up to a water depth of 10 m. The next step is taking directionally orientated core cutter samples of different depths from the sediment samples (II). Both types, horizontal and vertical samples, were taken in close proximity to one another. On these samples, falling head permeameter tests under laboratory conditions were performed (III) and thereby the hydraulic conductivities were determined (IV). Based on the determined vertical and horizontal hydraulic conductivities the hydraulic anisotropy can be calculated (V). To evaluate the performance of our new measuring approach, we compared the results with these of two established methods to determine the hydraulic conductivity of sediments, in situ permeameter tests and empirical methods based on grain-size distribution. Therefore, natural river bed sediment samples and samples taken out of an experimental container were used.

2 The new measurement approach

2.1 Freeze-core sampling

Conventional sampling techniques to extract water-saturated sands as well as unconsolidated silts and clays fail, if the cohesion of the sediment is very low. Whilst inserting and taking out the extraction device, the sample liquefies or is lost (Schreiner and

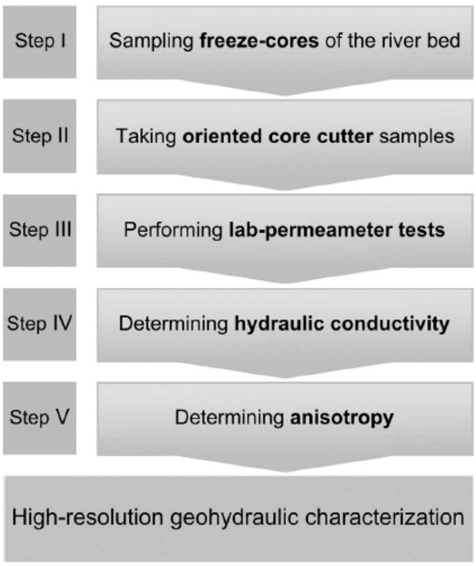

Fig. 1: Flow chart of our new approach to characterize the geohydraulic properties of river bed sediments presented in this study.

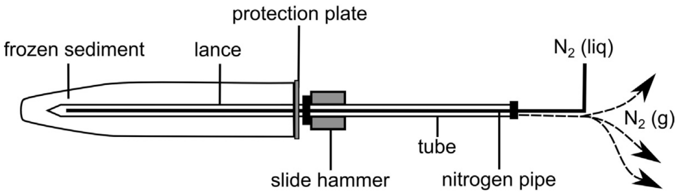

Fig. 2: Schematic illustration of the freeze-core sampler with its various elements (not in scale).

Fig. 3: The inner parts of a freeze-core. In this area, the sediment's natural structure is changed by probing.

Kreysing, 2013). Usually, this is accompanied by the destruction of the original sediment structure. The freeze-core technique allows the removal of undisturbed sediment samples, even if they have a low cohesion (e.g. Lisle, 1989). For this purpose, a hollow lance is inserted into the sediment. Liquid nitrogen flows through it for approximately 30–40 min, thereby freezing the surrounding sediment and forming a solid core (Fig. 2). The freeze-core diameter varies from 0.2 up to 0.5 m. The size depends on the grain-size distribution of the surrounding sediments. Furthermore, the expected diameter of the freeze-core is also linked to the freezing duration and the natural temperature of ground- and surface-water. The consumption of liquid nitrogen was about 40 L per core. For this study freezing lances between 0.8 and 1.5 m length were used to get sample material. Minor process-related disturbances of sediment happen with freeze-core sampling, too. Niederreiter and Steiner (1999) discovered that even the probing with a lance into the ground can cause a whirl up of fine-grained particles which are in immediate contact with the body of water. To reduce this effect, modified flow protection plates were used in our study or the sampling was conducted completely without protection plate. Thus, the hydraulic impulse induced by probing through the flow protection plate was weakened. Henceforth, no resuspension of fine-grained particles was observed. Furthermore, a contamination of the upper river bed's pore space by fine-grained particles is possible while using unmodified flow protection plates. With the described reduction of the hydraulic impulse and the combined elimination of the whirl-up this effect can possibly be counteracted as well. Depending on the grain-size distribution of the river bed, the driving of the lance can cause a disturbance of the sediment (Niederreiter and Steiner, 1999). The sediments next to the lance are pressed down during probing (Fig. 3). In this case, undisturbed samples can only be obtained from parts of the frozen core with sufficient distance to the freezing lance. Depending on the sediment composition, the disturbance-radius by the lance can be up to 3–6 cm. Freeze-cores with small diameters are often completely disturbed and consequently have to be excluded entirely. The effects caused by freezing sediment were investigated by Singh et al. (1982). They note that freezing and thawing has no significant impact on the volume or strength of water-saturated sand samples, if the displaced pore-water can flow out freely and the confining pressure remains constant throughout this process. Sego et al. (1994) described this effect of the freezing process of the surrounding sediment, too. They were able to show that the grain structure and pore space of sands and gravels withstood the freezing process, despite an approximately 9% volume expansion of ice.

2.2 Sample preparation

The frozen sediment was prepared for further tests after the removal of the freeze-core from the river bed. For this purpose, the obtained cores were dissected according to the field classification of the sediment and transported in a fridge to the laboratory. Here, the samples were wrapped in film and embedded in sand in frozen condition to ensure a constant confining pressure during thawing. This prevents drainage and thus settling. After defrosting, special horizontally and vertically oriented samples were taken with core cutters from the sediment body (Fig. 4). Samples from different depths allow for a depth-orientated core cutter sampling. Sampling was performed using stainless steel cylinders with a length of 50 mm and a diameter of 47 mm. A maximum wall thickness of 0.5 mm was used to minimize the disturbance of the sediment by the sampling process. Additionally, each end of the core cutters was given a clean edge to further mitigate disturbances. However, these are not entirely preventable. The conductivity is one of the most sensitive parameters concerning disturbances (Schreiner and Kreysing, 2013). So, a meticulous way of working is essential. The cylinder must be placed in a right angle in the sediment to avoid sidewall leakage in later hydraulic tests. Coarse grains, such as gravel and shells, hinder the taking of undisturbed core cutter samples and thereby limit the discussed method. The necessary sample amount relates to the maximum grain size encountered. The ratio between the maximum grain size and sample diameter or the sample height of sediments should be at least 1:10 for uniform or 1:5 for non-uniform sediments respectively (DIN 18130-1, 1998).

2.3 Lab permeameter tests to determine the hydraulic conductivity and anisotropy

In the laboratory, the hydraulic conductivity of the obtained sediment core cutter samples was determined by permeameter tests with falling head. In this study, this was executed in accordance with DIN 18130-1 (1998). The experimental set-up used is shown in Fig. 5. The conductivity is determined based on Darcy's law (1856):

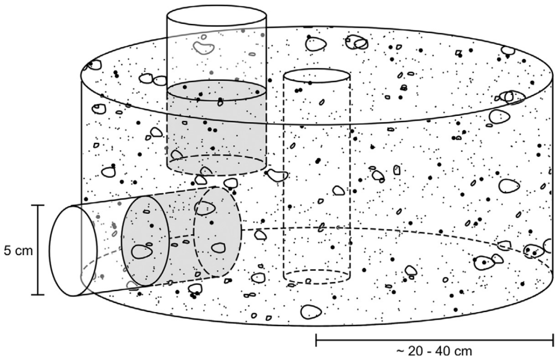

Fig. 4: Illustration of horizontal and vertical cores cut from the freeze-core (not to scale).

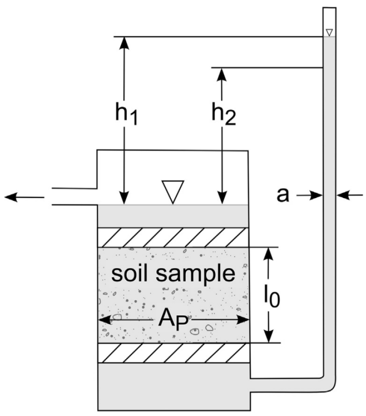

Fig. 5: Schematic experimental setup of a lab permeameter test with falling head according to DIN 18130-1 (1998).

$$K = \frac{a \cdot l_0}{A_p \cdot \Delta t} \cdot \ln\left(\frac{h_1}{h_2}\right) \tag{1}$$

with piezometer cross-section area a, sample height l_0, sample cross-section area A_p, measurement time Δt, tailwater level h_1 before and h_2 after the experiment. Because the dynamic viscosity of most fluids depends on temperature, an additional correction factor a was applied to the test results in order to refer the results to a water temperature of 10 °C. According to Langguth and Voigt (2004), this can be done for water as follows:

$$K_{10^\circ C} = \alpha \cdot K = \frac{1.359}{1 + 0.0337 \cdot T + 0.00022 \times T^2} \cdot K \tag{2}$$

The measured water temperature during the test is used for *T*. This conversion was performed in order to compare the results with those of the empirical methods, since they are calibrated to 10 °C.

3 Evaluation and application of the approach

3.1 Overview

In order to evaluate the results obtained with our measuring approach, two other methods to determine the hydraulic conductivity of sediments were carried out in the course of our study. One of these methods uses the grain-size distribution of the sample to empirically evaluate its conductivity. The second is the determination of the conductivity with in situ permeameter tests to verify the data. These in situ permeameter tests were conducted close to the freeze-core samples. Furthermore, other comparative tests were done in an experimental container under laboratory conditions. This was filled with sediment, which had an equivalent grain-size distribution to the natural river bed samples to compare the result of the field test with the comparative laboratory experiment. The effect of freezing and thawing was assessed by taking further freeze-core samples out of the experimental container and performing in situ permeameter tests in the same container.

3.2 Methods used for evaluation

3.2.1 K_g value calculated from grain-size distribution

To calculate the hydraulic conductivity K_g from grain-size distribution, sediment samples were dried at 100 °C for at least 24 h. Sieving separated the grains into 10 classes (<0.063 mm, 0.063–0.1 mm, 0.1–0.125 mm, 0.125–0.2 mm, 0.2–0.25 mm, 0.25–0.35 mm, 0.35–0.5 mm, 0.5–0.63 mm, 0.63–1.0 mm) (DIN 18123, 2011). The fractions start from a grain diameter of <0.063 mm, up to the coarse grains having a minimum diameter of 1 mm. K_g was estimated empirically based on the grain-size distribution. Multiple authors use parameters derived from this distribution (Bear, 1972; Zieschang, 1964; Köhler, 1965; Wittmann, 1981) The effective grain diameter d_x can be determined by the pelite content (*P*), a percentile of the cumulative grain-size distribution curve (for example, d_{10} is the diameter representing mass 10% passage through the sieve), or from the harmonic mean of the individual grain fractions (Matthes et al., 2012). In the scope of this work, several empirical approaches to calculate K_g were applied (Table 1). The methods according to Zieschang (1964), Köhler (1965) and Wittmann (1981) were selected additionally to the well-established and in the geotechnical field widely used techniques by Hazen (1893) and Beyer (1964). Köhler's and

Author	**Formula**			**Effec tive grain - dia-me-ter**	**Application domain**
Hazen (1893)	$K_g = 0.0166 \cdot d_{10}^2$	$c(u)$:	Empiric uniformity coefficient taken from Beyer's table	d_{10}	U < 5 0.1 mm < d_{10} < 3 mm
Beyer (1964)	$K_g = c(u) \cdot d_{10}^2$	c_1, c_2:	Empiric coefficient. In the given conditions: c1 = 0.0139 and c_2 = 1	d_{10}	U < 20 0.06 mm < d_{10} < 0.6 mm $2.0 \cdot 10^{-5} m/s$ < K_g< $4.0 \cdot 10^{-3} m/s$
Zieschang (1964)	$K_g = c_1 \cdot c_2 \cdot d_{10}^2$	τ	Kinematic viscosity ratio of water at 10 °C and water of differing temperature (if temperatures < 20 °C, then τ = 1)	d_{10}	U < 25 0.06 mm < d_{10} < 0.6 mm $2.0 \cdot 10^{-5} m/s$< K_g< $4.0 \cdot 10^{-3} m/s$
Köhler (1965)	$K_g = \frac{\tau}{r} \cdot 405 \cdot 10^{-4} \cdot \frac{e^3}{1+e} \cdot d_w^2$	r:	Roughness coefficient	d_W	
		e:	Void ratio		
		i:	Index of the individual grain fraction within freely selectable boundaries d_o and d_u		

	$\frac{1}{d_w} = \frac{\sum\left(\frac{1}{d_i} \cdot \Delta G_i\right)}{\sum \Delta G_i}$	ΔG_i :	Weight percentage of the individual grain fraction i		
		$\frac{1}{d_w}$	Reciprocal harmonic mean of the upper and lower boundary of the respective grain class i		
Wittmann (1981)	$K_g = \frac{0.0416 \cdot n^3 \cdot d_w^2}{(1-n)^2}$	n :	Porosity	d_W	$K_g \geq 1 \cdot 10^{-8} m/s$
		i :	Index of the individual grain fraction within freely selectable boundaries d_o and d_u		
	$d_w = \frac{100\%}{\sum\left(\frac{\Delta p_i}{d_i}\right)}$	Δp_i :	Mass percentage of the individual grain fraction		
		d_i :	Harmonic mean grain diameter of the respective grain fraction		

Table 1: Overview of different empirical methods to determine the hydraulic conductivity of sediments based on their grain-size distribution.

Fig. 6: Freeze-core taken from the river bed of the Sacrow-Paretz channel; sediment stratification visible.

Wittmann's method additionally take the porosity or the void ratio, into account. The porosity of the sediment sample (in natural sedimentation condition) was determined empirically by the sample volume in the core cutter, the sample's saturated mass, its dry mass and the density of the fluid (water) in the pore space.

3.2.2 In situ permeameter tests

Permeameter tests were performed to determine the vertical conductivity K_v of the upper part of the river bed. Additionally, in situ permeameter tests in the upper part of the river bed were performed to determine their vertical conductivity K_v. Hvorslev (1951) described the basic experimental setup of in situ permeameter tests. Since then, the method has been further developed by many authors, for example by Cheng and Chen (2007), Kennedy et al. (2008), Song et al. (2009) and Lu et al. (2012) to determine the hydraulic conductivity of river bed sediment. Chen (2000) developed a way to calculate the hydraulic anisotropy of river bed sediment with in situ permeameter tests. In our study, we used stainless steel tubes with a wall thickness of 1 mm and a diameter between 53 mm and 55 mm for infiltration experiments. Due to the small wall thickness, and the perpendicular insertion of the infiltration pipe into the river bed, the disturbance of the natural sediment structure can be assumed as negligible. If the infiltration pipe's penetration depth is several times larger than its diameter (Chen, 2000), the test can be analyzed using Darcy's (1856) approach. This criterion was met in all in situ permeameter tests. The penetration depth averaged 180 mm. Assuming a constant surface water level, the hydraulic conductivity of the sediment in the infiltration pipe can be calculated based on Darcy's law (1856) compliant with equation 1.

3.3 Field scale application–heterogeneous conditions

The undisturbed sediment samples used in this study were taken from the river bed of the Sacrow-Paretz channel (SPK), about 5 km north-west of the city of Potsdam (Brandenburg, Germany) (Fig. 6). The SPK is located in the Brandenburg Havel (Fig. 7) valley with its numerous lakes and is surrounded by the hills of terminal moraines from the Warthe and Weichsel glaciation (Wagenbreth and Steiner, 1990). They were formed by the retreat of the Weichselian glaciers in the Pleistocene as Zungenbecken (tongue-basins), proglacial lakes as well as tunnel valleys filled with glaciofluvial sediment (Hydrogeologie GmbH, 1993). The sectional anthropogenic SPK is located in a former glacial valley. The river bed consists of medium- to fine-grained Holocene valley sands. Sapropel, glacial till or landfill was also encountered depending on the location. In some parts, the upper layer of the river bed consists of several decimeter thick shell banks. During 3 sampling campaigns a total of 30 freeze-cores were removed from the river bed and 28 in situ permeameter tests were carried out in close proximity to the sampling points. Due to the local composition of the river bed (e.g. shell banks and armor stones) not all cores could be used for further tests. One vertically and one horizontally orientated core cutter sample was taken from the upper part i.e. the upper layer of the river bed of 17 cores. The horizontally orientated core cutter samples were taken close to the

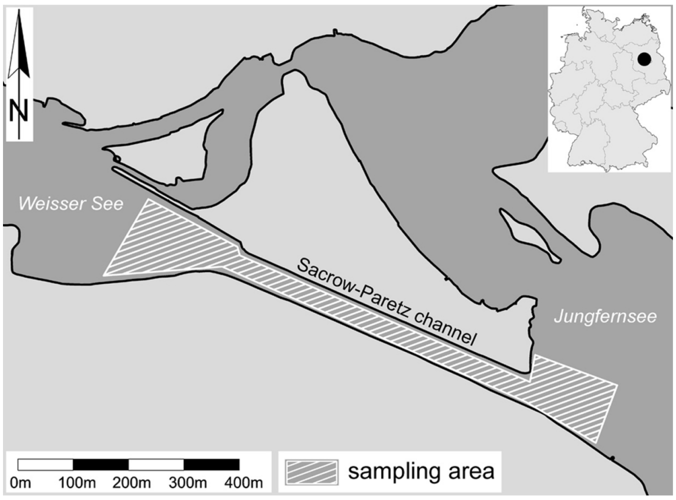

Fig. 7: The Sacrow-Paretz channel (SPK) is located about 5 km north-west of the city of Potsdam (Brandenburg, Germany).

vertically orientated ones. Lab permeameter tests with falling head were performed on these.

3.4 Laboratory scale application in a sediment filled container– homogeneous conditions

To assess the test results of the sediment samples extracted from the SPK, comparative experiments were conducted under

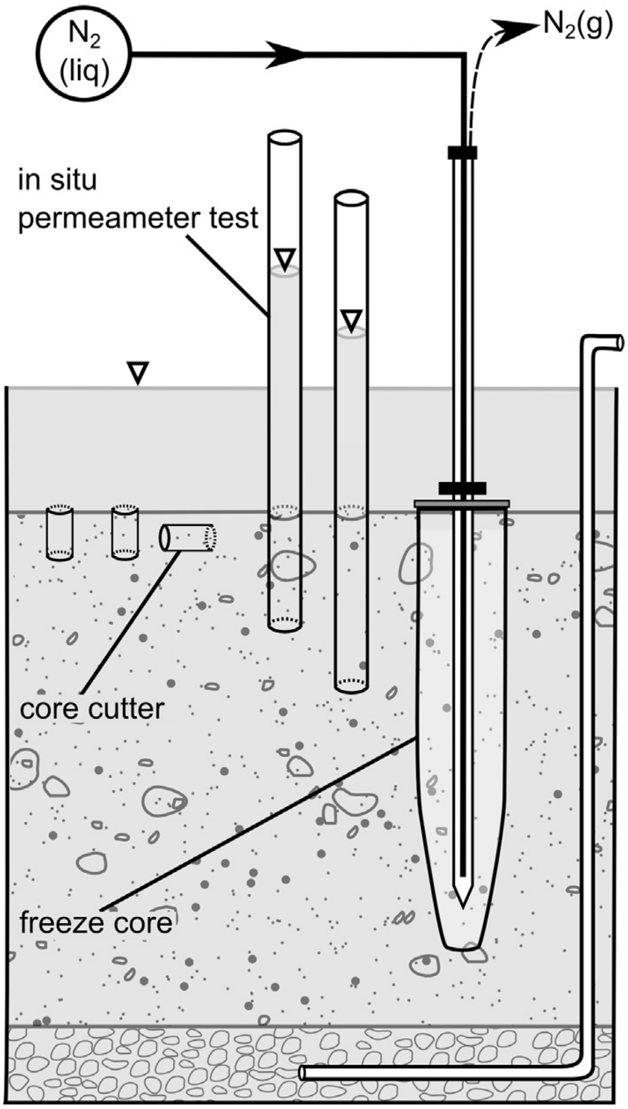

Fig. 8: Composition of the performed comparative tests (not to scale). In situ permeameter tests were executed; core cutter and freeze-core samples were taken in a sand filled test container.

laboratory conditions to accompany the field investigations. Up to 0.8 m of a 1 m high, cylindrical test container was filled with uniformly graded fine sand (Fig. 8). The grain-size distribution of the fine sand was similar to the sediment encountered at SPK to allow for a later correlation of the results. A thin coarse-grained drainage layer was installed previously at the bottom of the container. The fine sand was carefully saturated from the bottom up until the water level reached the top edge of the container. All experiments were carried out in the container, including extraction of a freeze-core as previously described. Furthermore, core cutter samples from non-frozen, but saturated zones of the test sand in the container were taken (Fig. 8). The removal of the core cutters was carried out from both the frozen and the non-frozen portion in vertical and horizontal orientation.

4 Results and discussion

4.1 Field scale application

Lab permeameter tests with falling head were performed on 17 vertically orientated core cutter samples. The results of these and of the in situ permeameter tests are shown in Fig. 9. The values determined with the two methods are consistent. However, compared to laboratory permeameter tests with falling head, the results of in situ permeameter tests display a higher variance. K_g values based on the grain-size distribution of the core cutter samples from freeze-cores were calculated by applying empirical formulas of different authors on the samples grain-size distribution. The techniques were carried out within their respective application domain (Fig. 9). In general, the empirical methods based on them yield higher conductivity values than the lab permeameter and the in situ permeameter test. Depending on which method was used, the values differ by a factor (K_g/K_v) between 29.4 (Hazen) and 9.8 (Wittmann) of those determined by lab permeameter tests with variable head. The highest (Hazen) and the lowest (Wittmann) empirically estimated Kg value differ by a factor of 3.0. To verify the applicability of our approach with regard to determine the anisotropy of natural sediments, 17 horizontally orientated core cutter samples were taken out close to the vertical ones. The hydraulic anisotropy (K_h/K_v) ranged between 0.8 and 15.9 depending on the position with a mean of 4.1.

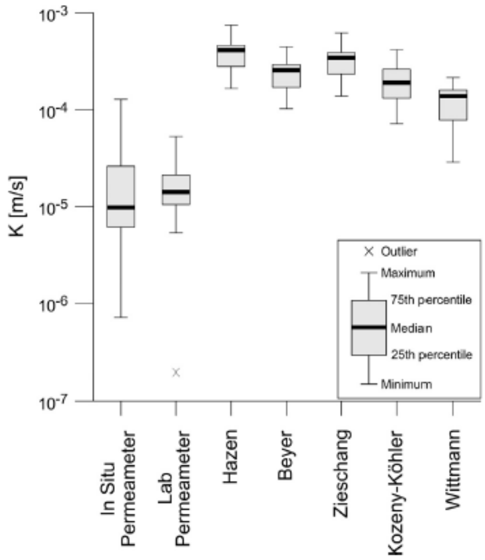

Fig. 9: Field scale application (natural sediment deposition) – box plots of K values determined by in situ permeameter tests, lab permeameter tests and of K_g values determined by empiric approaches of different authors based on the grain-size distribution of freeze-core samples.

4.2 Laboratory scale application

The results of the field application were compared with tests carried out in a sediment filled container. There is only a minor variance of the lab permeameter results between the differently taken core cutter samples. The comparative tests revealed no difference between samples from previously frozen sediment and those which had not been frozen (Fig. 10). The results of the

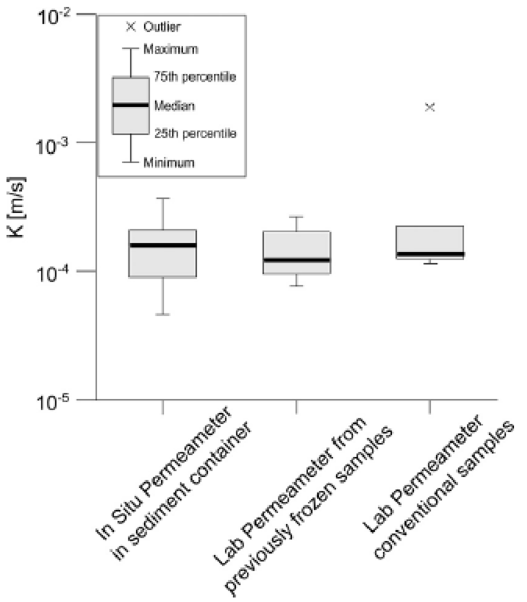

Fig. 10: Laboratory scale application (experimental container) – box plots of K_v determined by comparative experiments (in situ/lab permeameter tests of sediment and of previously frozen sediment).

in situ permeameter tests in the container correlate with those from lab permeameter tests, too. The median hydraulic conductivity determined with lab permeameter tests and in situ permeameter tests is $1.3 \cdot 10^{-4} m/s$. The empirically calculated values of K_g based on the grain-size distribution vary by a factor of 1.7 (Fig. 11). The method by Hazen (1893) yields the highest values (median: $6.4 \cdot 10^{-4} m/s$), the method by Wittmann (1981) the lowest (median: $7.7 \cdot 10^{-5} m/s$). Vertical and horizontal core cutter samples were cut out of the freeze-core from the test container. The values determined for K_v and K_h show no significant differences and diverge only by a factor (K_h/K_v) = 0.98.

4.3 Evaluation of the results and assessment of our new measuring approach

Several methods to determine the hydraulic conductivity of sediments were applied to verify the quality of our results. The hydraulic conductivities K_g calculated by empirical methods using grain-size distribution are considerably higher compared to the values of K determined by lab permeameter and in situ permeameter tests. This discrepancy does not depend on the empirical calculation or whether the samples were obtained from field tests or comparative experiments. Song et al. (2009) observed this discrepancy as well. During their investigations they detected deviations ranging from a factor (K_g/K_v) 1.2 to 6.6 depending on the empirical approach. Our field test results show an even more pronounced divergence amongst them, by a ratio of 9.8 (Wittmann), 13.5 (Kozeny-Koehler), 18.2 (Beyer), 24.6 (Zieschang) and up to 29.4 (Hazen). The comparative lab experiments on uniformly graded sand yielded ratios between 0.6 with the method of Wittmann and 5.0 using Hazen's formula. This is in accordance with the findings of Song et al. (2009). This discrepancy cannot be attributed to a non-compliance with the application boundaries of empirical methods, since all executed test were conducted within them. Due to the methodological approach of determining the grain-size distribution, the natural structure of the sediment and its natural bulk density is changed. For this reason potential hydraulic resistances caused by biofilms (cf. Rinck-Pfeiffer, 2000), bedding orientation of particles (cf. Cheng et al., 2013) or grain

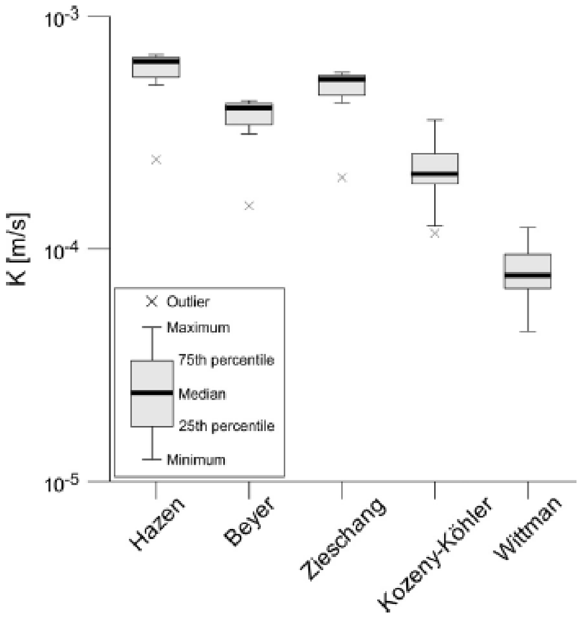

Fig. 11: Laboratory scale application (experimental container) – box plots of empiric values of K_g from comparative experiments.

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shape for example, are destroyed and not taken into account. Matthes et al. (2012) also observed discrepancies between the different methods. They noted that samples with a high percentage of fine fractions are more prone to error. Typical errors of sieve analysis are sieve loss and coagulation of the grains due to high moisture content in the sample. These uncertainties can also influence empirical methods applied to determine the hydraulic conductivity of sediment. This error propagation results in major inaccuracies. When strictly performing the laboratory work according to DIN 18123 (2011), most of the practical errors can be minimized. The mentioned aspects clearly show that in practice calculating K_g based on the grain-size distribution is not suitable, if the aim is to determine the natural hydraulic conductivity of river bed sediment in spatial high-resolution. The results of lab permeameter tests and in situ permeameter tests from this study differ only marginally. The field tests differ only by a factor of 0.69, the comparative lab experiment by 0.89. These small deviations are within the range of systematic errors of the process methodology. Neither technique significantly destroys the original sediment structure. Thus, it can be assumed that both methods allow the determination of the natural hydraulic conductivity of river bed sediment. In situ permeameter tests, however, can establish the vertical hydraulic conductivity of the upper layer of the river bed. The higher variance of the results of our in situ permeameter tests compared to these of our lab permeameter tests shows a higher uncertainty of this method. However this method is quick and easy to execute and provides initial data concerning the vertical hydraulic conductivity and their spatial variability. A measuring method developed by Chen (2000) enables the estimation of the horizontal conductivity. The horizontal conductivity analysis is restricted to selected accessible orientations and positions, i.e. banks, slopes and steps, due to the experimental set up. Moreover, it is not possible to determine the hydraulic conductivity in multiple depths from the same position. Vertical and horizontal conductivities, furthermore, can only be measured in moderate proximity. Chen's approach does not facilitate a vertically and horizontally highly–resolved hydraulic characterization of sediment. Our method presented in this paper avoids this barrier. The river bed's hydraulic conductivity can be determined in vertically and horizontally oriented high-resolution, if freeze-cores from the river bed along with core cutter samples from the freeze-cores are taken. This also enables a small-scale detection of the anisotropy of the sediment conductivity in the tested region. Similarly, a targeted determination of potential hydraulic resistances, for example of thin clay layers, is possible. No natural sedimentary structures are disturbed when applying the presented method, apart from the sediment close (a few cm) to the lance (cf. Fig. 3). Bulk density and porosity are not changed. Hydraulic resistances which remain undetected by grain analysis are revealed. In the course of our study, we conducted preliminary tests in the test area and in a test container to check if the anisotropy is measurable with the approach. The container experiment yielded a significantly lower mean anisotropy of 0.98 as well as a low mean variation compared to the test area, which had a factor of 4.1. Naturally deposited sediment is prone to layering and other previously mentioned effects causing hydraulic resistance resulting in anisotropic conditions. For these reasons discrepancies between the test-environments are plausible. So, the method's fitness to determine the anisotropic hydraulic conductivity of river bed sediments both quantitatively and qualitatively was demonstrated in this comprehensive study. The comparative tests showed that freezing and thawing had no negative effect on the results. Core cutter samples from previously frozen sediment showed no difference to those of tests on accompanying samples which had not been frozen. Methodological errors can be minimized by taking specimens in a meticulous manner.

5 Conclusions

A detailed knowledge of the geohydraulic properties of river bed sediments is vital concerning the assessment of the effect of hydraulic engineering on adjoining aquifers. Many different methods are devoted to the geohydraulic characterization of sediments. However, all of these have unique advantages and disadvantages relating to the geohydraulic characterization of river bed sediments. Some destroy the natural sediment structure, others lack a small scale resolution and all fail to determine the immediate anisotropy. Our presented approach starts at this boundary. In this paper we introduced our new measuring approach for an improved hydraulic characterization of river bed sediments based on freeze-core samples. Falling head lab permeameter tests were performed on vertical and horizontal core cutter samples which were taken from the freeze cores to determine the hydraulic conductivity and the anisotropy on a small-scale. The approach was tested on natural sediments from the Sacrow-Paretz channel (SPK) and from samples taken from an experimental container. Two well established methods, empirical determination based on grain-size distribution and in situ permeameter tests were additionally applied to evaluate our results reached with our approach. In the course of this study, our conclusions can be summarized as follows:

- Empirical methods based on grain size distribution are not suitable for determining the in situ conductivity of river bed sediments because the empirically calculated hydraulic conductivities are considerably higher compared to the values of K_v determined by lab permeameter and in situ permeameter tests.
- The results of the performed in situ permeameter tests and these of the lab permeameter tests done on core cutter samples are consistent. Both methods are able to determine the hydraulic conductivity in the sediments natural deposition structure.
- Our new measuring approach enables an improved geohydraulic characterization of river bed sediments including the determination of the anisotropy. None of the other methods can resolve the hydraulic conductivity on a small-scale in vertical and horizontal orientation.

Further research will be devoted to the application of our presented approach in order to verify its ability to characterize the river bed on a large scale and validate the method under different hydraulic boundary conditions. In a first step, the approach will be comprehensively applied to the sediment research at Sacrow-Paretz channel. In doing so, its ability to work on a large scale will be checked, due to the high effort related to the method, in the laboratory but also in the field. In a further step, the method shall be applied in locations with differing ground and hydraulic boundary conditions as well with coarse sediments. Understanding river–aquifer exchange fluxes is vital when assessing local and regional water balances. Our on-going freeze core sampling in accordance with other investigations have demonstrated that river–aquifer exchange fluxes tend to be strongly spatially variable. Some authors have addressed this still open-ended research question and tried to estimate to which degree river bed heterogeneity has to be represented in a model in order to achieve reliable estimates of river–aquifer exchange fluxes (Kurtz et al., 2013). Until now, this question has been addressed based on synthetic simulation experiments, which mimic the river bed's hydraulic characteristics. The herein presented freeze-core

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technique was designed to deliver field estimates of the small scale vertical variability. Numerous sampling at different locations is expected to deliver further needed geostatical information (mean, variance, correlation length, etc.) to develop effective parameters for the representation of the river–aquifer exchange fluxes at the river–groundwater management scale.

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