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Hydraulic Experiments for Determination of In-situ Hydraulic Conductivity of Submerged Sediments

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A new type of in-situ hydraulic permeameter was developed to determine vertical hydraulic conductivity (VHC) of saturated sediments from hydraulic experiments using Darcy's law. The system allows water to move upward through the porous media filled in the permeameter chamber driven into sediments at water-sediment interface. Darcy flux and hydraulic gradient can be measured using the system, and the VHC can be determined from the relationship between them using Darcy's law. Evaluations in laboratory and in field conditions were performed to see if the proposed permeameter give reliable and valid measures of the VHC even where the vertical flow at water-sediment interface and fluctuation of water stage exist without reducing the accuracy of the derived VHC. Results from the evaluation tests indicate that the permeameter proposed in this study can be used to measure VHC of saturated sandy sediments at water-sediment interface in stream and marine environment with high accuracy.

Understanding the interaction between river water and groundwater could be critical at preventing flooding hazards triggered potentially by heavy rain, storm, or hurricane. In addition to the characteristic property for hydrogeological matrix, hydraulic conductivity in river bed and bank can be a measure of water intrusion rate through the river bank and groundwater in such events, resulting in potential destruction of the bank and following catastrophic hazards. In another aspect, the interaction between surface water and groundwater can be also a critical issue for managing subsurface contamination especially in fluvial and/or coastal areas. If the subsurface is contaminated with radioactive materials, the emphasis on the interaction cannot be overstated especially in proximity of nuclear power plant and nuclear waste storage sites. The important hydrogeologic property of aquifer, hydraulic conductivity ranges over several orders of magnitude and varies spatially randomly and is anisotropic in direction[1]. An accurate measurement of vertical hydraulic conductivity (VHC) of the sediment at water-sediment interface is essential in the analysis of the interaction between surface water and groundwater. However, the measurement of hydraulic conductivity has been challenging in the vertical as well as horizontal directions. In an effort to estimate the vertical hydraulic conductivity, variety of approaches have been made, including numerical modeling[2,3], pumping tests[4,5], tracer tests[6,7], and physical in-stream methods[8–10].

In-stream methods of determining VHC include slug tests, in-situ permeameter tests, and seepage flux measurements with seepage meters coupled with measurement of hydraulic gradient through the streambed[8]. Field permeameter and the coupled seepage meter measure VHC, whereas slug tests measure horizontal hydraulic conductivity. Landon *et al.*[8] compared those in-stream methods for measurement of streambed VHC, and pointed out that all of those techniques had some uncertainties. Lu *et al.*[9] mentioned the effects of vertical flow across water-sediment interface and of surface water level fluctuation on the accuracy of hydraulic conductivity during the field tests. It was also reported that there might be a limited applicability for the seepage meter coupled with hydraulic gradient measurement to determine streambed VHC in relatively high-energy flowing streams with high sediment mobility[8]. In order to complement the shortcomings of the coupled seepage meter with hydraulic gradient measurement for determination of streambed VHC, Kelly and Murdoch[10] have developed a device called piezo-seep meter which uses a pan with a single piezometer along its axis.

The objectives of this study are to design a simple, cost-effective instrument that can be used to measure VHC of submerged sandy sediments, and to evaluate its field applicability even where vertical flow exists in the upper streambed and/or the stream stage fluctuates without reducing the accuracy of the derived VHC. In this study, an alternative method for measuring VHC of sediments at water-sediment interface is suggested and results of laboratory and field tests are presented for verification of the newly designed methodology.

Methods

Permeameter design. In order to determine VHC using Darcy's law, measurements of volumetric flow rate (discharge, Q $[L^3/T]$) and hydraulic gradient (dh/dL $[L/L]$) should be available. The proposed permeameter is designed to measure these two parameters simultaneously on site. The permeameter consists of two main components: a rigid open-bottom chamber and a cylinder (Fig. 1). These two components of the permeameter are interconnected with a flexible tube. The cylinder is a top-open hollow pipe with cone-shaped edge at its bottom. It is used to measure the volumetric flow rate from the chamber to the cylinder, and to induce upward water flow through sediments in the chamber. The chamber has open bottom and closed top to isolate potential upward flow from the sediment toward the open water body across the water-sediment interface. Manometers connected to the chamber are used to measure the difference in hydraulic head between vertically separated two points in the chamber.

The key feature of the proposed permeameter is the method to drive the upward water flow from the chamber. Figure 2 schematizes the inducement of upward flow of water in the chamber. As shown in Figure 2a, water level in the tubing connected to the chamber presents the hydraulic head in upper end of the chamber that was vertically installed in the sediment. It is summed up by elevation head and pressure head, and mathematically expressed like below:

$$h = z + \psi = z + \rho g(h_1 + h_2) \tag{1}$$

where h = hydraulic head $[L]$, z = elevation head $[L]$, ψ = pressure head $[L]$, ρ = the density of fluid, and g = the acceleration of gravity.

When the groundwater system in the chamber is under hydraulic equilibrium, hydraulic head at the lowermost part is equal to that at the uppermost part of the chamber. When the tubing from the chamber is connected to the inlet of the cylinder, and the elevation of the cylinder inlet is adjusted to be placed at the point b shown in Figure 2b, the total hydraulic head at the inlet of the cylinder will be lower than that in Figure 2a by $\rho g h_1$. The hydraulic head at the inlet of the cylinder is equal to that at the uppermost part of the chamber, but lower than that at the lowermost part of the chamber by $\rho g h_1$. Changes in hydraulic head within the chamber like this cause the upward flow of water within the chamber, and eventually from the chamber to the cylinder. If difference in head is maintained constant, the volumetric flow rate and hydraulic gradient in the chamber will be also constant. These two parameters can be measured simultaneously on site with the proposed permeameter. The volumetric flow rate can be calculated by measuring increase of water column in the cylinder multiplied by the cross sectional area of the cylinder during the planned time period. A pressure transducer is installed at bottom of the cylinder to measure the increase in height of water inside the cylinder. Hydraulic heads at two points in the chamber can be measured with manometers attached at the side of the chamber (Fig. 1). When the driving force is applied constantly, the volumetric flow rate and hydraulic gradient should be constant and the relationship between Darcy flux and hydraulic gradient should be linear. These are because Darcy's Law is valid only for laminar flow.

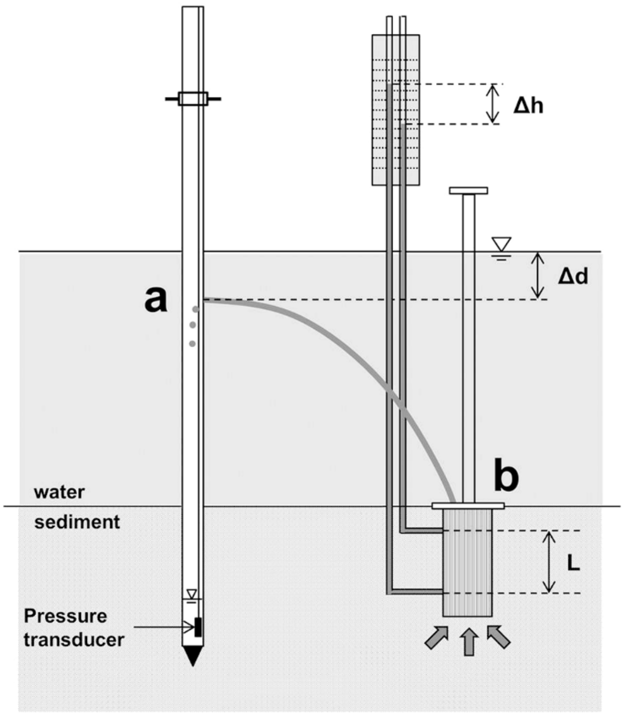

Figure 1 | Schematic diagram of the proposed field permeameter. (a) A vertical cylindrical pipe and (b) a rigid open-ended chamber. They are interconnected with a flexible tube.

Evaluation in the laboratory. Laboratory-scale experiments were conducted to evaluate if the proposed permeameter gave reliable and valid measures of the VHC of sediments, where the vertical flow exists across water-sediment interface or does not exist. Following experimental setup suggested by Belanger and Montgomery[11] with slight modifications, a cylindrical tank with 140 cm height and 140 cm inner diameter was used for the experiments (Fig. S1). The tank was filled with two beds of gravel (15 cm thick layer bed of the coarse gravel at bottom and 15 cm thick layer bed of the fine gravel above) and a 60 cm-thick bed of clean sand (Table 1). The gravel beds were supported with a permeable plate (5 cm thick) above the bottom of the tank. The permeameter chamber was made with a steel pipe with 40.1 cm in length, 21 cm in inner diameter, and 0.1 cm in thickness, and was inserted into the sand bed at a depth of 40 cm. Two ports with one-touch fittings were installed in the side of the chamber, at the upper and the lower positions, with 20.1 cm apart from each other, and located at 10 cm from the double ends of the chamber. An outlet at the top of the chamber was connected to the cylinder with polyurethane tubing (inner diameter of 0.4 cm, outer diameter of 0.6 cm) to measure volumetric flow rate from the chamber into the cylinder. Water levels of the bucket and the tank were kept to be constant by overflowing water through the outlets at top parts of them. Upward or downward water flow through the beds in the tank was controlled by adjusting the elevation of the bucket, which was connected to the tank inlet at the center of the tank bottom with flexible tubing. If the head of the bucket is higher than that of the test tank, upward seepage through the beds in the tank is generated. But if the head of the bucket is lower than that of the tank, downward seepage through the beds in the tank is generated. There is no upward or downward seepage, if the head of the bucket is same with that of the tank.

At first, we compared two methods for determination of the hydraulic conductivity: the proposed method and laboratory constant head test. Both methods were applied for the same sand used in the tank test. The apparatus for the laboratory constant head test was equipped with a column (4.8 cm in diameter and 45 cm in height) and two constant head reservoirs. By adjusting vertical distance between the two reservoirs, the volumetric flow rate of each experimental step could be changed. In the tank test, the head of the bucket was adjusted to be the same as that of the tank. To induce water flow through beds in the chamber, the Δd was set to be 20 cm below the water level in the tank. Volumetric flow rate and head difference were measured manually using a graduated cylinder and manometers, respectively. A series of following experiments were performed by increasing Δd from 20 cm to 80 cm with an increment of 20 cm.

In order to assess whether the measures of VHC with the proposed permeameter are valid under vertical flow conditions, eight tests were performed with the test tank by varying the ΔH and/or Δd. Firstly, we adjusted the ΔH, the relative head of the bucket to that of the water in tank. Secondly, we set the Δd below the water level in tank, and measured the flow rate and difference in head. We changed the Δd from 20 cm to 100 cm with an increment of 20 cm, and repeated the measurements of the flow rate and head difference at each Δd. This was the first set of the eight tests. The same procedures were repeated seven times for different ΔH. We lowered the ΔH from 41.3 cm to −20.3 cm with a decrement of 10 cm. For the last run, ΔH was set to −29.6 cm. Volumetric flow rates and head differences were manually measured as above mentioned.

Evaluation in the field. Field evaluation of the system was carried out in beach of Bangdu Bay located in the eastern part of Jeju Island, South Korea. Bangdu Bay is a semi-enclosed bay, with an area of approximately 0.6 km^2 and a mean depth of approximately 3 m (Fig. S2), and shows the seepage rates from 45 to 48 cm per a day in the entire bay[12]. Tidal range is about 3 m during spring tide and 0.8 m during neap tide. Beach sediments of the bay consist mainly of medium to coarse sands and fine gravels.

Three tests were conducted during neap tide in September 13, 2013 to measure the hydraulic conductivities of the sediments of the bay at different tide levels as shown in Figure 3. Experiments were performed with an interval of about 1 h from low to high tide, and the tidal height of each test was 113, 133, and 156 cm at 11:40 am, 12:30 pm, and 13:30 pm, respectively. The system was deployed at the position approximately 30 m seaward of mean tide. The chamber of the permeameter used in the field test was 13.4 cm in diameter and 40 cm in length. Two ports with one-touch fittings were installed in the side of the chamber, at the upper and the lower positions, with 20 cm apart from each other, and located at 10 cm from the double ends of the chamber. The cylindrical pipe for measuring volumetric flow rate was 4.8 cm in diameter and 150 cm long. These two components of the permeameter were made with steel and inter-connected with flexible polyurethane tubing with inner diameter of 0.4 cm and outer diameter of 0.6 cm. A series of measurements for volumetric flow rates and hydraulic gradients was performed at the same point where the chamber of the system was deployed into sediments. The volumetric flow rates were calculated from water level recorded at 5 s intervals with a pressure transducer, and head differences were measured using manometers. Because of waves, the Δd was set approximately at a depth of 10, 20, 30, and 40 cm below the sea water level during the each test.

Results

From the first laboratory test, Darcy flux measured by the proposed permeameter ranged from 0.003 to 0.006 cm/s, and hydraulic

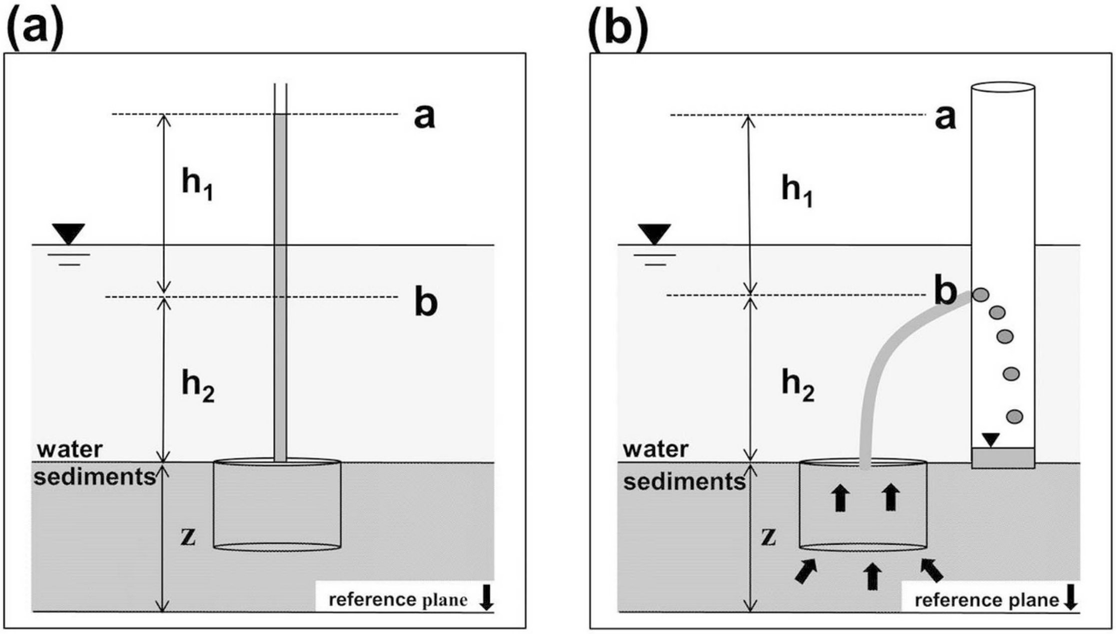

Figure 2 | **Schematic representation of the upward water flow from the chamber to the cylinder.** (a) Water level in the tubing, representing the hydraulic head in upper end of the chamber. (b) Upward water flow induced by adjusting relative elevation of the cylinder inlet to that of the water level in the tubing.

gradient ranged from 0.025 to 0.05. In comparison, Darcy flux from the constant head test ranged from 0.04 to 0.111 cm/s, and hydraulic gradient ranged from 0.269 to 0.621 (Table S1). Although both Darcy flux and hydraulic gradient measurements showed different scales from the laboratory test and the constant head test, nearly linear relationships were observed between Darcy flux and hydraulic gradient from both the methods (Fig. S3). The hydraulic conductivities from the two tests were nearly same, with 0.2 and 0.14 cm/s respectively for the constant head test and the laboratory test using the permeameter proposed in this study.

From the second laboratory test, a total of 40 measurements for the Darcy flux and hydraulic gradient were obtained using the proposed permeameter and the results were summarized in Table S2. Darcy flux and hydraulic gradient ranged from 0.003 to 0.015 cm/s, and from 0.01 to 0.09, respectively. The point *K* values ranged from 0.147 to 0.317 cm/s with the average and standard deviation values of 0.19 ± 0.034 cm/s. The histogram of the point *K* values from the 40 measurements are shown in Figure S4. Most of point *K* values fall in the range of 0.17–0.21 cm/s, with the highest frequency at 0.19 cm/s. The linear *K* determined from the whole measurement data is 0.15 cm/s (Fig. S5). This linear K is the slope of the regression line with *R* value of 0.96. Figure S6 represents the relationships between Darcy fluxes versus hydraulic gradients from the each test with different ΔH. The linear *K* values from the each test ranged from 0.14 to 0.23 cm/s.

From the field tests, a total of 12 measurements of the Darcy flux and hydraulic gradient were acquired using the proposed permeameter. Figure 4 shows the water level changes in the cylinder during the multiple tests. The linear increase of water level in the cylinder indicated that the water flow from the chamber was steady. The point *K* values ranged from 0.024 to 0.037 cm/s with the average and standard deviation of 0.031 ± 0.004 cm/s. The linear *K* values determined from the each test were 0.028, 0.032, and 0.036 cm/s, while the linear *K* value from the linear regression for the total measurements was 0.03 cm/s with *R* value of 0.95 (Fig. 5).

Table 1 | Grain size distribution of sand used for the laboratory experiments

Grain size (mm)	Fraction (%)	Classification
0.031–0.062	5	Coarse silt
0.062–0.125	11	Very fine sand
0.125–0.250	7	Fine sand
0.250–0.500	30	Medium sand
0.500–1.000	48	Coarse sand

Discussion

The system proposed in this study is a constant head permeameter. The measuring procedure of the method is almost same with the laboratory constant-head test except the driving force to flow water through column filled with porous materials. Water flow through the column in laboratory constant head test is driven by gravity, while in the proposed permeameter by the induced hydraulic head difference between the upper end and the lower end of the chamber. The

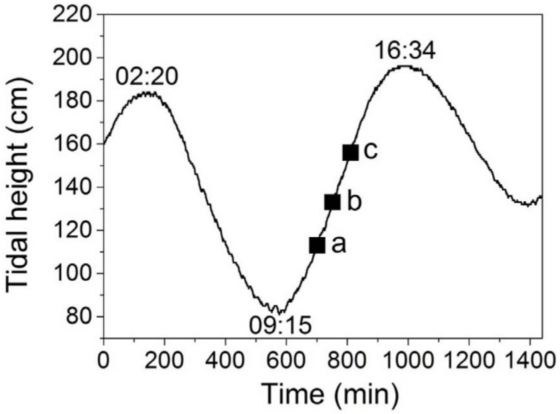

Figure 3 | **Tidal data at the Sungsan tidal station near the Bangdu Bay for September 13, 2013, and the black rectangular points indicate the times and tidal heights of three tests which took place from low-to-high tide period.**

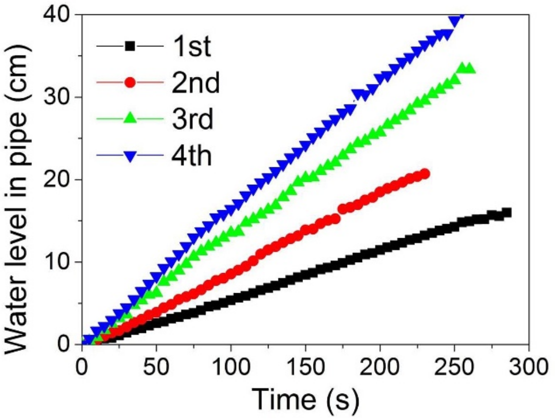

Figure 4 | Linear increase of water levels in the cylinder, indicating steady water flow from the chamber, namely laminar flow.

hydraulic pressure distribution in the chamber of the proposed permeameter can be finely controlled by adjusting the elevation of the cylinder inlet to be placed at a lower position than the hydraulic head in the chamber. This improves the accuracy of measurement of flow rate and hydraulic gradient with the permeameter. This approach was also similar to the piezo-seep meter method described by Kelly and Murdoch[10], with a few important differences. They reported that VHC measured with the piezo-seep meter were 1.6 to 10 times greater than the values measured by pumping tests. They used a battery-powered diaphragm pump to impose a flow rate on the system. We suspect that the method to impose a flow rate on the system would influence the ability to control finely the volumetric flow rate of the system. No electric power is needed to impose a flow rate on the proposed system.

Darcy fluxes and hydraulic gradients measured with the proposed permeameter were compared to those by the laboratory constant head permeameter. The hydraulic gradient and Darcy flux by the proposed permeameter were one order of magnitude lower than those by the laboratory constant head permeameter. This means that measurement of hydraulic conductivity with high resolution is possible using the proposed method. Nearly linear relationships between Darcy fluxes and hydraulic gradients measured with the above two methods suggested that water flows in the chamber filled with sediment were laminar, and the hydraulic conductivities determined from those two variables were fully complied with the Darcy's law. No significant difference in hydraulic conductivity measurements was found between the test methods. All of the above mentioned results imply that the hydraulic conductivity measurements with the proposed permeameter are valid.

Repeated measurements of hydraulic conductivity under different conditions in laboratory and in field with the proposed permeameter produced consistent results. Especially, the tests in Bangdu Bay, Jeju where vertical flow across water-sediment interface and tidal fluctuation of seawater co-exist, drive the conclusion that the field applicability of the proposed permeameter is pertinent, and the resulting measurements are not only reliable but also valid. The ability to control directly the hydraulic conditions inside the chamber improves the field applicability of the permeameter.

The Hvorslev falling-head permeameter test was considered the most robust method for measuring K of the upper portion of the streambed because of the inherent limitations of the empirical grain-size methods and less sediment disturbance for permeameter than slug tests[8]. But if vertical flow exists in the upper streambed or the stream stage fluctuates during the falling head permeameter tests, the accuracy of the derived hydraulic conductivity could be reduced[9]. In the case of gaining stream, the hydraulic head of groundwater in the upper streambed is at a higher elevation than the surface water level.

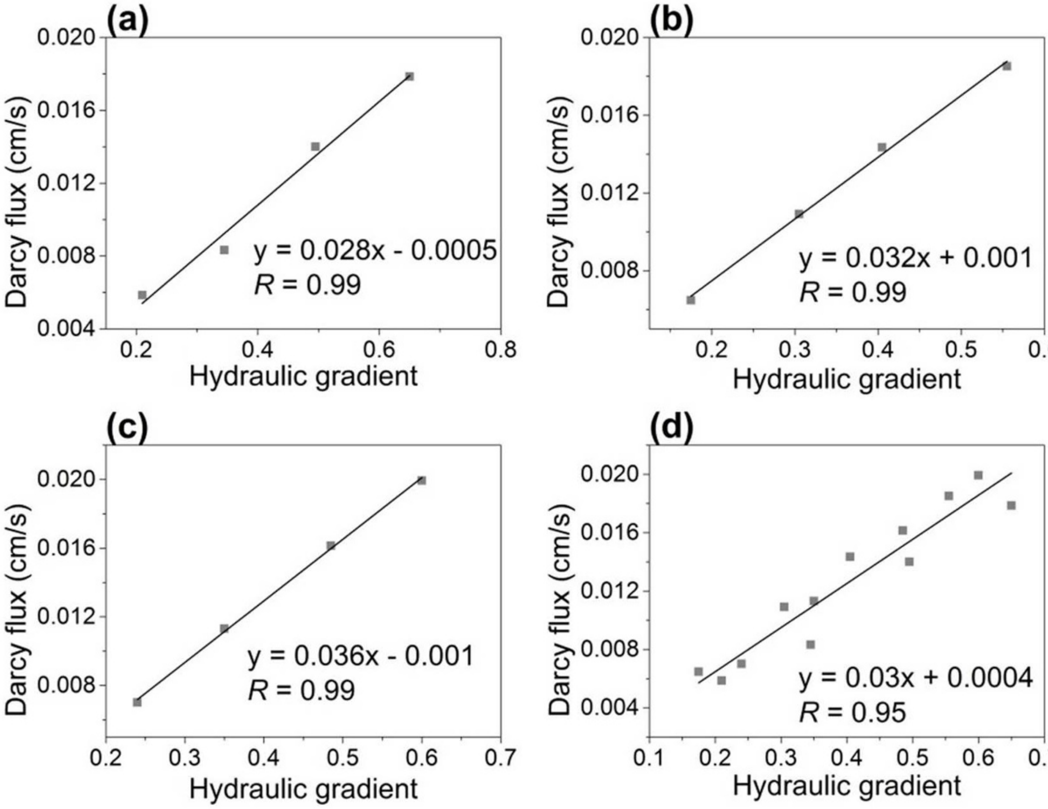

Figure 5 | Linear relationships of Darcy fluxes vs. hydraulic gradients measured from the field permeameter test. (a, b, c) Results of the test a, b, and c as shown in Figure 3. (d) Linear regression for the total measurements from the three tests.

This is the opposite for losing stream where the head of groundwater in the upper streambed is at a lower elevation than the surface water level. The proposed permeameter can induce upward flow of groundwater through sediments in the chamber regardless of the surface water level, and of the magnitude and the direction of seepage. This will nearly always be realized if only the inlet of the cylinder is placed at a lower elevation than the groundwater head in the chamber driven into the sandy sediments. If the groundwater flow in the chamber is laminar, the hydraulic gradient and Darcy flux measured with the proposed permeameter will be maintained constant. These were identified from the field tests.

In this work, a new method to determine the hydraulic conductivity of submerged sandy sediments was proposed and evaluated in laboratory and in field. The hydraulic conductivity measurements with the permeameter were reliable and valid even where vertical flow and surface water level fluctuation co-existed. This is because the driving force to impose a flow rate on the system can be controlled to overcome the effects of the above mentioned hydraulic conditions. This feature of the system will also enable to measure directional hydraulic conductivity. Vertical hydraulic conductivity and hydraulic gradient measurements with this system can also be used to calculate seepage flux of water across surface water-sediment interface. The proposed permeameter is simple, cost-effective and easy to use in field, but inherently limited to measurements of the hydraulic conductivity of the upper portion of submerged sediments. Measurement of hydraulic conductivity of sediments exposed above surface water level is another challenging issue. Collectively, the proposed permeameter can provide an alternative approach to analyze the interaction process at water-sediment interface in stream, lake, and near-shore marine environment.

1. Bear, J. *Dynamics of Fluids in Porous Media* 123–124 (American Elsevier, New York, 1972).
2. Sophocleous, M., Koussis, A., Martin, J. L. & Perkins, S. P. Evaluation of simplified stream-aquifer depletion models for water rights administration. *Ground Water* **33**, 579–588 (1995).
3. Yager, R. M. Estimation of hydraulic conductivity in a riverbed and aquifer system near the Susquehanna River, Broome County, New York. *USGS Water Supply Paper*, 2387 (1993).
4. Hantush, M. S. Wells near streams with semipervious beds. *J Geophys Res.* **70**, 2829–2838 (1965).
5. Hunt, B. Unsteady stream depletion from ground water pumping. *Ground Water* **37**, 98–102 (1999).
6. Harvey, J. W. & Bencala, K. E. The Effect of streambed topography on surface-subsurface water exchange in mountain catchments. *Water Resour Res.* **29**, 89–98, doi: 10.1029/92WR01960 (1993).
7. Hart, D. R., Mulholland, P. J., Marzolf, E. R., Deangelis, D. L. & Hendricks, S. P. Relationships between hydraulic parameters in a small stream under varying flow and seasonal conditions. *Hydrol Process.* **13**, 1497–1510 (1999).
8. Landon, M. K., Rus, D. L. & Harvey, F. E. Comparison of instream methods for measuring hydraulic conductivity in sandy streambeds. *Ground Water* **39**, 870–885 (2001).
9. Lu, C., Chen, X., Cheng, C., Ou, G. & Shu, L. Horizontal hydraulic conductivity of shallow streambed sediments and comparison with the grain-size analysis results. *Hydrol. Process* **26**, 454–466, doi: 10.1002/hyp.8143 (2012).
10. Kelly, S. E. & Murdoch, L. C. Measuring the hydraulic conductivity of shallow submerged sediments. *Ground Water* **41**, 431–439, doi:10.1111/j.1745-6584.2003.tb02377.x (2003).
11. Belanger, T. V. & Montgomery, M. T. Seepage meter errors. *Limnol. Oceanogr.* **37**, 1787–1795 (1992).
12. Hwang, D.-W., Lee, Y.-W. & Kim, G. Large submarine groundwater discharge and benthic eutrophication in Bangdu Bay on volcanic Jeju Island, Korea. *Limnol. Oceanogr.* **50**, 1393–1403, doi: 10.4319/lo.2005.50.5.1393 (2005).

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Author contributions

B.J.L. conceived the study and designed experiments. B.J.L. and J.H.L. wrote the manuscript. B.J.L., H.Y. and E.L. performed the experiments. All authors discussed the results and reviewed the manuscript.

Additional information

Supplementary information accompanies this paper at http://www.nature.com/scientificreports

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