International Journal of Undergraduate Research and Creative Activities

Volume 9 Article 4

September 2017

Designing and Evaluating the Quality and Cost-effectiveness of Saturated Sediment Permeameters

Caleb Gibson
St. Ambrose University, gibsoncaleba@sau.edu

Nicole Woodall
St. Ambrose University, woodallnicoled@sau.edu

Caleb Reiter
St. Ambrose University, reitercalebt@sau.edu

Susa H. Stonedahl
St. Ambrose University, stonedahlsusah@sau.edu

Recommended Citation
Gibson, Caleb; Woodall, Nicole; Reiter, Caleb; and Stonedahl, Susa H. (2017) "Designing and Evaluating the Quality and Cost-effectiveness of Saturated Sediment Permeameters," *International Journal of Undergraduate Research and Creative Activities*: Vol. 9, Article 4.
DOI: http://dx.doi.org/10.7710/2168-0620.1093

Designing and Evaluating the Quality and Cost-effectiveness of Saturated Sediment Permeameters

Designing and Evaluating the Quality and Cost-effectiveness of Saturated Sediment Permeameters

Peer Review

Abstract

Many simulations require accurate measurements of saturated hydraulic conductivity, a sediment property that governs the speed at which water flows through sediments relative to head differences. The goal of our project is to design and build an inexpensive permeameter capable of producing accurate hydraulic conductivity values. We tested four permeameters; a standard research grade constant-head permeameter, a falling-head permeameter modeled off of an *in situ* stream method, a constant-head permeameter made out of 4” PVC pipe, and a similar constant-head permeameter made out of 2” PVC pipe. Our custom-built constant-head permeameters both utilized a U-shaped design, two tubes which form a manometer, and multiple output overflows. Despite significant differences in design, method, and cost, we found that all four of the permeameters yielded relatively consistent mean hydraulic conductivities with low standard deviations (0.004-0.019). We also compared the attributes: price, weight, and number of parts. Our conclusion is that because the average K-value and standard deviation of each design is within reason, the best choice depends on the practitioner’s situation and intention.

Keywords

Permeameter, Hydraulic Conductivity, Design

Acknowledgements

We thank Dr. Michael Opar, Dr. Kris Eitrheim, and Shawn Jackson for construction assistance, Dr. Andrew Lutz and Dr. Forrest Stonedahl for reviewing our paper, and Dr. Katie Trujillo and Vickie Logan for organizing the St. Ambrose Undergraduate Summer Research Institute experience. We also thank the Stoffel Fund for Excellence in Scientific Inquiry and the donors of the St. Ambrose Undergraduate Summer Research Institute for funding.

INTRODUCTION

Hydraulic conductivity (K), also known as permeability, is a value used to describe the ease with which water flows through sediments. It is related to the size, roughness, and water saturation level of the sediment (Hillel, 1980; Bear, 1972; Klute, 1965). Hydraulic conductivity is quantified using Darcy's Law as the ratio of velocity to the hydraulic head gradient, giving it dimensions of length over time. It is an important factor affecting flow through sediments under streams and rivers (Packman and Salehin, 2003; Elliot & Brooks, 1997a). Modeling the flow through the sediments is dependent on K and is crucial to understanding nutrient transport (Triska et al., 1989) and the fate of contaminants (Harvey & Fuller, 1998), which affects water quality and the health of ecosystems (Jones & Mulholland, 2000). Specifically, in this study we investigated ways to measure the hydraulic conductivity of fully saturated sediments, such as those found under a stream or river.

Hydraulic conductivity is typically measured with either a constant-head or falling-head permeameter (Landon et al., 2001; Klute, 1965; Genereux et al., 2008). Both types of permeameters use head differences to create flow through sediment. For the constant-head systems, the water levels do not change and the volumetric flow rate through the system is measured. For the falling-head system the higher water level falls and the time it takes to drop is used to calculate K (Landon et al., 2001 Conners, 2012).

Many studies (Stonedahl et al., 2010; Stonedahl et al., 2012; Marion et al., 2008; Salehin et al., 2004, Elliot and Brooks, 1997b; Sawyer, 2009; Buffington & Tonina, 2009) require hydraulic conductivity values. Our research group found methods to measure the K-value that were expensive (Humboldt 2016B; Gilson; 2016, Eijkelkamp, 2016) and methods, which we could not reproduce with precision or accuracy (Conners, 2012). The absence of easily accessible, inexpensive and simply constructed permeameters motivated the objective of this study: to design and construct an inexpensive and accurate permeameter. To accomplish this goal, we built three inexpensive permeameters and compared their measured K-values with one another and to results from a standard research-grade permeameter.

MATERIALS AND METHODS

For our standard research-grade permeameter, we purchased a constant-head permeameter from the Humboldt Manufacturing Company (Humboldt, 2016b). We designed our first custom permeameter as a laboratory adaptation of the classic in situ falling-head field method (Landon et al., 2001). Second, we designed and built a constant-head permeameter out of 4" PVC pipe using a U-shape to keep the sediment in place. Third, we constructed a slightly modified, smaller and lighter version of the 4'' PVC permeameter out of 2" PVC pipe. All four permeameters are described in more detail in sections 2.1-2.4. We used fine grain silica sand for all measurements. Our sieve analysis produced a size distribution of D10: 0.285 mm, D30: 0.361 mm, D60: 0.475 mm (Hillel, 1980). We determined the porosity to be 0.38 by adding a known volume of sand to water in a graduated cylinder (Conners, 2012).We collected data in each permeameter on ten different days after repacking the sediment. On each of these days we repeated each measurement five times. Test environment conditions were considered as water viscosity varies with temperature and affects the flow of water through permeameters. We corrected our data for the temperature variations following the method shown in Hillel (1980). We then compared the

DOI: http://dx.doi.org/10.7710/2168-0620.1093

measurements from the Humbolt permeameter to the three custom designs.

2.1 Humboldt Permeameter

2.1.1 Humboldt Constant-head Permeameter Materials

The Humboldt permeameter is a manufactured constant-head apparatus designed to measure K-values. We purchased three components from the Humboldt Manufacturing Company. The main component is the permeameter cell (HM-5804), which contains the sediment sample. It uses a system of pervious plates and a spring to hold the sediment in place in a six-inch diameter cylinder, and it has a small spout with a valve through which the water leaves the system. The second component is a double manometer stand (HM-5861). The third component is a constant-head tank for our intake water (HM-5880). This tank provides the upper level constant-head and keeps air bubbles from being transferred to the main chamber (Humboldt, 2016a). This permeameter is illustrated in Figure 1 and the parts are listed in Table 1. The total cost of this permeameter was around $1200.

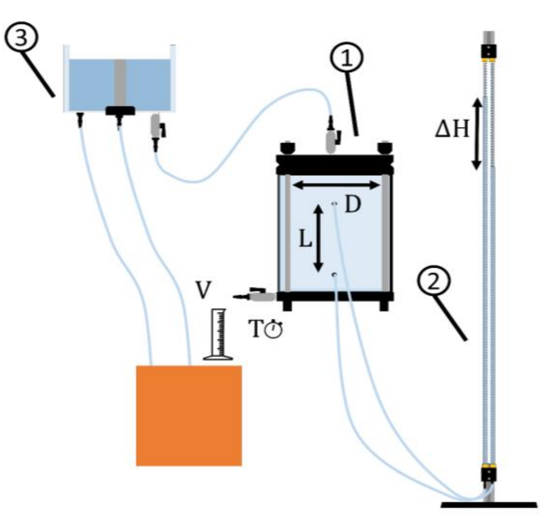

Figure 1. Humboldt constant-head permeameter data collection schematic and part designation. Part numbers for use with Table 1.

Table 1. Parts list for Humboldt constant-head permeameter

Part #	Item	Quantity	Size
1	Constant-head cell (HM-5804)	1	6''
2	Dual Manometer Stand (HM-5861)	1	4'
3	Constant-Head Tank (HM-5880)	1	

2.1.2 Humboldt Constant-head Permeameter Methods

Before each trial, we filled the permeameters with water. Then, we carefully removed all air bubbles from the tubing to prevent faulty readings (Humboldt, 2016a). Next, we filled the main chamber with sand and put the pervious plates and spring into place. After tightening the apparatus lid, we checked for air bubbles and repeated the process until all air bubbles had been removed. We let the system and an extra reservoir of water sit overnight to allow the sand to settle and ensure the water was a uniform temperature.

Before collecting data, we let the water flow for an hour. We measured the volumetric flow rate, Q, by collecting water from the outflow in a graduated cylinder for a measured amount of time. We repeated this data collection five times. We also measured both head levels using the manometer and calculated their head difference, ΔH. Then we calculated the hydraulic conductivity Equation 1 (Landon et al., 2001),

$$K = \frac{QL}{A\Delta H} \quad \rightarrow \quad K = \frac{4QL}{\pi D^2 \Delta H} \qquad \textit{Equation 1}$$

where D is the diameter of the cell, L is the length between the two head level spouts, and A is the cross-sectional area. These parameters are illustrated in Figure 1.

2.2 Falling-head Permeameter

2.2.1 Falling-head Permeameter Materials

The assembled falling-head permeameter is shown in Figure 2. The main component of this apparatus is a cylindrical glass vase, with a 10’’ diameter and 24’’ height. The second component is a 30’’ long 2’’ diameter clear tube, with an adhesive measuring tape attached to the outside. The total cost of this setup was $68.81.

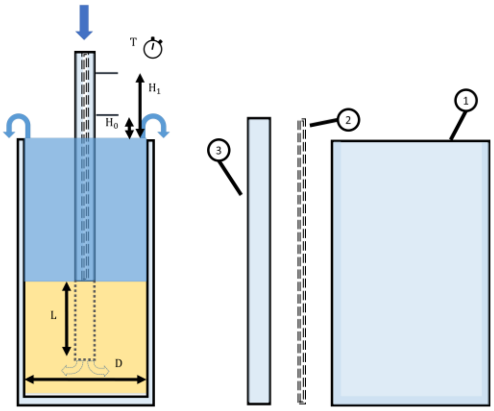

Figure 2. Falling-head permeameter data collection schematic and expanded part view. Part numbers for use with Table 2.

Table 2. Parts list for falling-head permeameter

Part #	Item	Quantity	Size
1	Vase	1	20" x 24"
2	Adhesive Tape	1	2" x 30"
3	Clear Tube	1	2" x 30"

2.2.2 Falling-head Permeameter Methods

Falling-head permeameters are commonly used in field studies (Landon et al., 2001). We modified the method described in Landon et al. (2001) for use in a laboratory setting by using a large vase instead of a stream. We set up the falling-head permeameter by first partially filling the vase with water. Then we carefully scooped 33 to 37 cm of sand into the apparatus while ensuring that the water level remained above the settling sand at all times to avoid trapping air bubbles in the sand. Excess water flowed over the rim of the vase into a catch basin, keeping this water level constant at the rim of the apparatus. We then inserted the smaller (2" diameter) tube into the center of the sand using a level to guarantee the tube remained vertical as we pushed it approximately 20 cm into the sand (trials varied from 17.4-22.2 cm). We also filled a 5-gallon bucket with water, so that the water would be the same temperature when we used it during data acquisition. The apparatus and bucket were then left untouched overnight to ensure the sand settled.

When collecting data, we used a pitcher to pour water from the 5-gallon bucket into the top of the tube to create a higher head level. We filled the tube higher than our starting head level (33.6 to 32.8 cm above water level). Then we recorded the amount of time it took for the water level in the tube to drop three inches for five repetitions. As the water level fell in the tube, water flowed over the edge of the apparatus into the catch basin. K was calculated using Equation 2 [*Landon et al.*, 2001; *Hvorslev*, 1951],

$$K = \frac{\frac{\pi}{11}D+L}{t}\, ln\frac{H_0}{H_1} \qquad \text{Equation 2}$$

where D is the diameter of the glass vase, L is the length of tube submerged in the sediment, t is the time between measured head levels, H_0 is the upper head level and H_1 is the 3-inch lower head level. Our setup and our data collection parameters are shown in Figure 2.

2.3 PVC Constant-head Permeameters

2.3.1 4-inch PVC Constant-head Permeameter Materials

The 4” PVC permeameter was constructed from PVC pipes and joints as shown in Figure 3. We connected the parts using both purple primer and regular clear PVC cement. The adhesive substances were applied liberally to make certain we did not have any leaks in our final apparatus. Leaks would impair the integrity of the design and invalidate data collection. Our 4” PVC design has two possible outflow spouts, so that we can measure K using two different flowrates. It would be possible to add more outflows as long as they are not higher than the input overflow level. We constructed a large wooden stand for the 4” PVC permeameter to allow the device to stand upright and ensure vertical measurements. An itemized parts list is provided in Table 3. The cost of the 4” PVC permeameter without the wooden stand was $71.79.

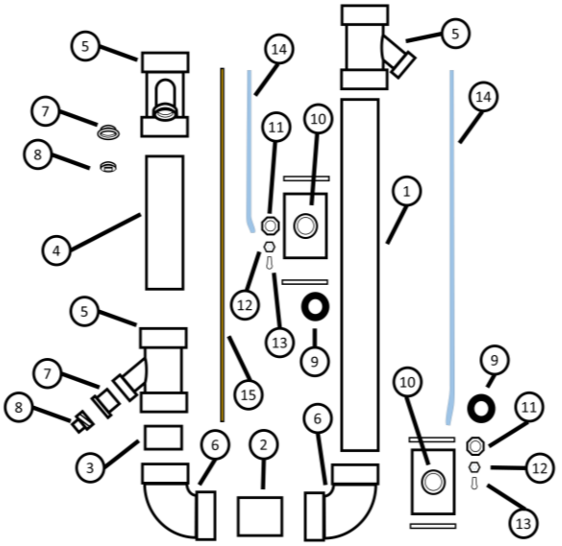

Figure 3. 4” PVC constant-head permeameter expanded part view. Part numbers correspond to Table 3.

2.3.2 2-inch PVC Constant-head Permeameter Materials

Figure 4 shows the design and parts of the 2” PVC permeameter. The materials chosen for the 2’’ PVC permeameter were primarily the 2” equivalents of the 4” parts. The most notable alterations we made were the addition of a third overflow and the replacement of standard white PVC pipe with clear PVC pipe on the side of the apparatus we filled with sand. We chose to use clear pipe because it allowed us to observe the sediment and any changes in condition during the test. We added a third overflow level to allow more variations in head level. The 2” PVC permeameter was supported by a large ring stand. Table 4 shows all of the parts we used to construct the apparatus. The 2” permeameter cost $93.49. If regular PVC pipe had been used in place of the clear pipe the price would have been $53.91, with functionally equivalent measurement capabilities.

Table 3. Parts list for 4’’ PVC constant-head permeameter

Part #	Item	Quantity	Size
1	PVC Pipe	1	4'' x 37''
2	PVC Pipe	1	4'' x 4''
3	PVC Pipe	1	4'' x 2-1/2''
4	PVC Pipe	1	4'' x 14''
5	PVC 45 Deg Tee	4	4"
6	90 Deg PVC St Elbow	2	4"
7	PVC Cleanout Adapter	2	1-1/2x1/2
8	PVC Cleanout Plug	2	4"
9	Rubber Washer	2	3/4 x 2-1/4 x 1/8
10	Saddle Tee Assembly	2	2" x 1/2" (3/4" spigot)
11	Size Reducer	2	2" - 1-1/2"
12	PVC Female Adapter	2	3/4"
13	3/8" Barb x 1/2" MIP Elbow	2	3/8 - ½
14	Vinyl Tubing	1	1/2" x 20'
15	Meter Stick	1	3'

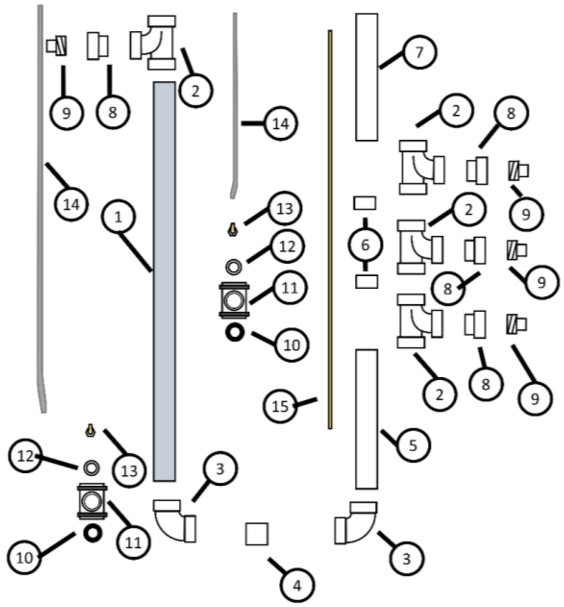

Figure 4. 2" PVC constant-head permeameter expanded part view. Part numbers correspond to Table 4

2.3.3 PVC Constant-head Permeameter Methods

Constant-head methods are the widely accepted laboratory methods for quicker flowing sediments, like sand (Conners, 2012). We chose to include a U-shape in our designs in order to hold the sand in place without filters that could affect the flow of the water. The original 4" PVC permeameter was designed, built, and tested first. Then we built the smaller (2") permeameter to see if we could obtain similar results, while overcoming the size and weight constraints of the original design.

The constant-head permeameters were set up with the same general procedure. We moved the recirculation tube away from the overflow to allow access to the top during filling. We capped the overflow spouts, while filling the permeameter with water to keep the sand submerged at all times. We slowly scooped sand into the permeameter until the sand level was significantly above the hole in the apparatus for the upper head level manometer tube. Usable data requires the sand level to remain above the hole after settling. We made sure that the water level tubes were attached to a vertical measurement instrument (graduated tube or meterstick). We secured the recirculation tube into the top overflow. We also filled the bucket below the input overflow with water to allow it to reach the same temperature as the water in the apparatus. The permeameters were both left to sit overnight to verify the sand was settled.

Table 4: Parts list for 2'' PVC constant-head permeameter

Part #	Item	Quantity	Size
1	Clear PVC Pipe	1	2" x 48"
2	PVC Tee	4	2"
3	90 Deg PVC St Elbow	2	2"
4	PVC Pipe	1	2" x 2"
5	PVC Pipe	1	2" x 13"
6	PVC Pipe	2	2" x 1"
7	PVC Pipe	1	2" x 12"
8	PVC Cleanout Adapter	4	2"
9	PVC Cleanout Plug	4	2"
10	Rubber Washer	2	3/4 x 2-1/4 x 1/8
11	Saddle Tee	2	2" x 1/2" (3/4" spigot)
12	PVC Female Adapter	2	3/4"
13	1/2" Barb x 3/4" MIP Elbow	2	3/4" - 1/2"
14	Vinyl Tubing	1	1/2" x 20'
15	Meterstick	1	3"

We started the testing procedure for both the 2" and 4" permeameters by turning on the pump in the reservoir to start recirculating the water at the input overflow.

DOI: http://dx.doi.org/10.7710/2168-0620.1093

Water not immediately entering into the system was recycled into the reservoir creating a constant overflow level. We then opened the highest output spout. Once the water had travelled through the sand column, it exited through one of the output overflow spouts into a basin. A member of our team periodically emptied the basin back into the input reservoir. We created a manometer to measure the head difference, ΔH, by attaching two tube assemblies atop small drilled holes spaced 50 cm apart on each apparatus to measure the head at each location. A schematic of data collection for both devices can be found in Figures 5 and 6.

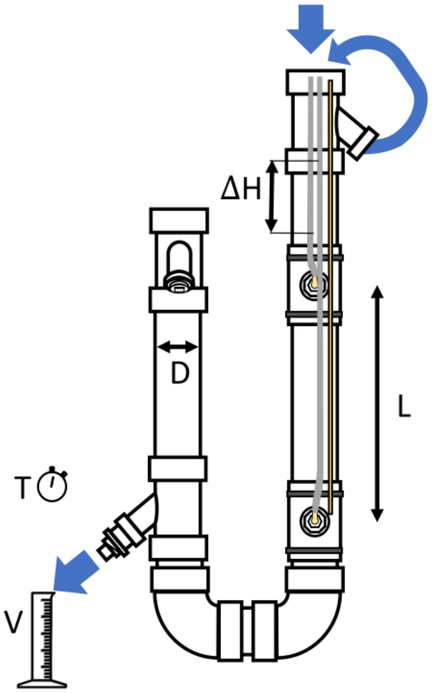

Figure 5. 4” PVC constant-head permeameter data collection schematic

Before testing, we let water flow through the permeameters for at least an hour. After that time, we recorded the volume of water discharged for a measured amount of time and measured the H. This data was collected five times per sample for each overflow level after allowing the permeameter to run for an hour between overflow levels.

For the 2” and 4” PVC permeameters we had five K-values from each overflow level for each day of measurements. In order to reduce multiple measurements to a single K-value we rearranged Equation 1 into Equation 3 and plotted the average QL vs. AΔH for each head level.

$$(A\Delta H)K = QL \qquad \textit{Equation 3}$$

In this form, the K-value can be calculated as the slope of the resulting trend-line, which was forced to pass through the origin. An example of this for each permeameter is shown in Figure 7.

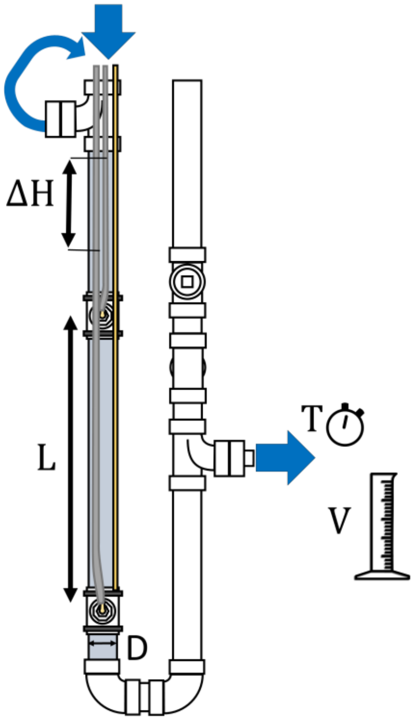

Figure 6. 2” PVC constant-head permeameter data schematic

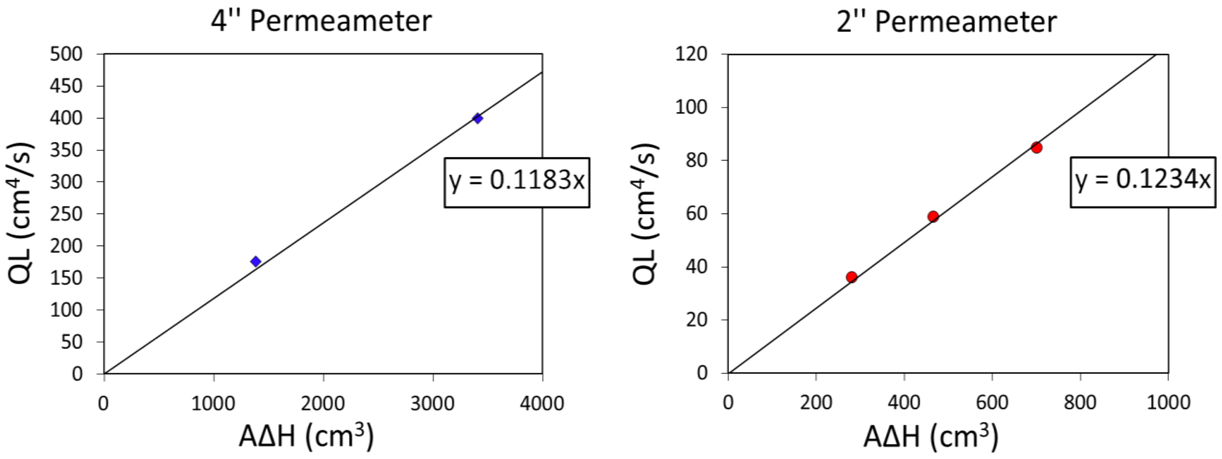

Figure 7. 4” PVC and 2” PVC constant-head permeameters graphs with K-values given as the slope of the trend lines. Average data from 5 trials at each head level from one day of trials is shown.

RESULTS

The key parameters that we assessed were average K-value, standard deviation of the K-values, price, weight, sample size, and number of parts (Table 5). The similarity between average K-value indicates the accuracy of a method, as evaluated by comparison to the other methods. The standard deviation shows us precision within these methods. We recorded the weight of each apparatus as another factor affecting the ease of use. This is particularly important for the PVC permeameters, which needed to be lifted to be emptied between samples. We also included the amount of sediment needed to conduct a test. This could be very important, when sediment quantities are limited. The number of parts required is included as a metric of how complex the device was to assemble.

CONCLUSIONS/DISCUSSION

We found that all four methods yielded similar results. The mean hydraulic conductivity values were close together with small variations between tests for all of the permeameters. Each method has advantages and disadvantages, which make it better

Table 5. Permeameter comparison metrics

Permeameter	K-Value	Standard Deviation	Cost	Sample Size	Weight	# of Parts
Humboldt	0.117	0.011	$1311	3648 cm^3	9.5 kg	3*
Falling-head	0.115	0.019	$69	15059 cm^3	39 kg	15
2” PVC	0.126	0.004	$54 / $103**	2331 cm^3	9.1 kg	3
4” PVC	0.115	0.016	$72	9323 cm^3	30 kg	14

* Number of separate items purchased

**Clear PVC

DOI: http://dx.doi.org/10.7710/2168-0620.1093

suited for particular situations. While a single superior method was not found, it was determined that an expensive permeameter is not required to achieve research-grade readings.

Despite being purchased assembled, the Humboldt permeameter was not simple to use nor did it preform significantly superior to other methods. It also had a significantly larger price ($1311) than the other permeameters. Despite these drawbacks, the Humboldt permeameter also had some strengths. It required the smallest sample size and is more commonly accepted than the other methods for reporting values in publications.

We found the falling-head permeameter to be the simplest method. Only three components need to be purchased, which makes setting this up very easy. However, the large amount of sediment required for this test could be an obstacle. In this method the sediment could be scooped out of the vase making the weight less important than it is for the PVC permeameters. While the average K-value was consistent with the other four permeameter designs, it has the lowest precision. This means more trials would need to be run to ensure a good value. This method appears to be best suited to situations that are more exploratory in nature, with large amounts of available sediment.

The constant-head permeameters require the most preparation to construct, but give similar values to the Humboldt with low standard deviation at a low cost. Specifically, the 4” PVC permeameter K-value within 0.002 cm/s of the Humboldt and had a standard deviation in the middle of the group. This particular method required a large amount of sediment to operate and there was not an easy way to change the sediment without lifting all of it at once, which was cumbersome. Flow rates, especially at the lower overflow level, were very fast. While the method gives acceptable values, assembly was laborious and the necessity of lifting its large weight to change the sediment could be a drawback.

The 2” PVC permeameter required the same construction and operational procedures, but greatly diminished the weight. The addition of clear pipe improved our ability to observe the sand and any changes that occurred in it. The standard deviation was the smallest of all the permeameters. The average K-value of this permeameter, however, was the largest, and farthest from the group. The difference is small, but could demonstrate a bias due to the small size of the tube.

Overall our project was to evaluate our custom permeameter designs and determine if they could be used in place of expensive alternatives. Our results suggest that our custom designed permeameters worked as well as the expensive manufactured permeameter. Each method has strengths and weaknesses, which may make any one of them the best choice for a given situation. While more trials should be done using different sands or other types of sediment, our initial results suggest that all three custom permeameters, if used properly, will produce good results with most sands and gravels.

REFERENCES

Bear, J. (1972), Dynamics of Fluids in Porous Media. Dover Publications.

Buffington, J., and D. Tonina (2009), Hyporheic exchange in mountain rivers, part II: Effects of channel morphology on mechanics, scales, and rates of exchange, *Geogr. Compass*, 3(3), 1038–1062, doi:10.1111/j.1749-8198.2009.00225.x.

Conners, J. A. (2012), *Groundwater for the 21st Century*. McDonald & Woodward Pub. Co.

Eijkelkamp (2016), Soil and Water. Laboratory equipment https://en.eijkelkamp.com/products/laboratory-equipment/

Elliott, A. H. and N. H. Brooks (1997a), Transfer of nonsorbing solutes to a streambed with bed forms: Theory, *Water Resources Research*, *33*(1), 123-136.

Elliott, A. H. and N. H. Brooks (1997b), Transfer of nonsorbing solutes to a streambed with bed forms: Laboratory, *Water Resources Research*, *33*(1), 137-151.

Genereux, D. P., Leahy, S., Mitasova, H., Kennedy, C. D., Corbett, D. R., (2008), Spatial and temporal variability of streambed hydraulic conductivity in West Bear Creek, North Carolina, USA. *J. Hydrol*. 358, 332-353, doi: 10.1016/j.jhydrol.2008.06.017

Gilson Company Inc. (2016), Granular Soil Permeameters https://www.global-gilson.com/granular-soil-permeameters

Harvey, J. W., and C. C. Fuller (1998), Effect of enhanced manganese oxidation in the hyporheic zone on basin-scale geochemical mass balance, *Water Resources Research*, 34(4), 623-636.

Hillel, D. (1980), Fundementals of Soil Physics, *Sandiago, CA: Academic Press Inc*

Humbolt Manufacturing. (2016a), Constant Head Tank, 1500cc. https://www.-humboldtmfg.com/constant-head-tank.html

Humbolt Manufacturing. (2016b), Permeameters for Permeability Testing. https://www.humboldtmfg.com/permeameters.html

Hvorslev, M.J. (1951), Time lag and soil permeability in ground-water observations. U.S. Army Waterways Experiment Station Bulletin 36, Vicksburg, Mississippi.

Jones, J. B. and Mulholland (Eds.) (2000), Streams and Groundwaters. Academic Press, San Diego, CA

Klute, A. (1965), Laboratory measurement of Hydraulic conductivity of saturated soil, *Methods of soil analysis*, 9, 210-221.

Landon, M. K., D. L. Rus, and F. E. Harvey (2001), Comparison of instream methods for measuring hydraulic conductivity in sandy streambeds, *Ground Water*, 39(6), 870-885, doi: 10.1111/j.1745-6584.2001.tb02475.x.

Marion, A., A. I. Packman, M. Zaramella, and A. Bottacin-Busolin (2008), Hyporheic flows in stratified beds, *Water Resources Research*, 44 W09433, doi:10.1029/2007WR006079

Packman, A. I. and M. Salehin, 2003. Relative roles of stream flow and sedimentary conditions in controlling hyporheic exchange. In *The Interactions between Sediments and Water* (pp. 291-297). Springer Netherlands. doi: 10.1007/978-94-017-3366-3_40

Salehin, M., A. I. Packman, and M. Paradis (2004), Hyporheic exchange with heterogeneous streambeds: Laboratory experiments and modeling, *Water Resources Research*, 40(11), doi:10.1029/2003WR002567.

Sawyer A. H. and M. B. Cardenas (2009), Hyporheic flow and residence time distributions in heterogeneous cross-bedded sediment, *Water Resources Research*, 45(8), doi: 10.1029/2008wr007632.

Stonedahl S. H., J. W. Harvey, A. Wörman, M. Salehin, and A. I. Packman (2010), A multiscale model for integrating hyporheic exchange from ripples to meanders, *Water Resources Research*, 46, W12539, doi: 10.1029/2009WR008865

Stonedahl, S. H., J. W. Harvey, J. Detty, A. Aubeneau, and A. I. Packman (2012), Physical controls and predictability of stream hyporheic flow evaluated with a multiscale model, *Water Resources Research*, 48, W10513, doi:10.1029/2011WR011582

Triska, F. J., V. C. Kennedy, R. J. Avanzino, G. W. Zellweger, and K. E. Bencala (1989), Retention and transport of nutrients in third-order stream in northwestern California: Hyporheic processes, *Ecology*, 70(6), 1893–1905.