Falling head permeability tests on Till deposits from the Vale of Eden, England - supplementary report including new data

Geotechnical and Geophysical Properties and Processes Team: UK Rocks and Soils

Internal Report IR/14/007

BRITISH GEOLOGICAL SURVEY

Geotechnical and Geophysical Properties and Processes Team

INTERNAL REPORT IR/14/007

Falling head permeability tests on Till deposits from the Vale of Eden, England - supplementary report including new data

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) to investigate the physical properties of till deposits that occur in the United Kingdom. This report is a factual account of a laboratory assessment of permeability on till deposits from the River Eden Demonstration Test Catchment (EdenDTC) area. It duplicates Internal Report IR/13/034 (Morgan et al., 2013) and includes additional data from a further series of tests carried out in September 2013. The work was done as part of the BGS research programme: Physical Properties of UK Rocks and Soils project under the Geotechnical and Geophysical Properties and Processes Team (BGS/NERC project NEE4584).

Contents

FIGURES

TABLES

Summary

This report describes permeability tests carried out on twenty three samples of glacial till obtained from boreholes drilled in the Vale of Eden area in Cumbria, England. The results of 134 initial tests are also documented in Internal Report IR/13/034 (ibid.). Further samples were obtained in September 2013 and results of an additional 76 tests on seven additional samples are reported here. The report outlines the testing procedure and presents the results of the permeability tests. The laboratory permeability values of till soils from the Moreland and Pow Focus Catchments ranged from 10^{-5} to 10^{-10} m/s, suggesting permeability is variable, with Medium Low to Impermeable soils.

1 Introduction

Permeability tests carried out on 23 samples of Till from the Eden Valley area of Cumbria. Samples were obtained from boreholes drilled by DEFRA from two catchments 'Pow' and 'Dedra Banks'. The tests were carried out according to the procedure in Section 10.7 of Head (1994), with only minor modifications to specimen dimensions. The test is neither a British nor an American standard, but is generally accepted. The BH locations are listed in Table 1 below.

Table 1: Sample locations

Site name	BH Name	NGR_East	NGR_North
Pow Catchment	BH1	339544	550161
	BH2	339534	550135
	BH3	339312	550188
	BH6	338854	550028
	BH7	338703	550091
Dedra Banks (Moorland Catchment)	BH1	357903	519550
Hill House Nook 2013	BH2	338775	549952
	BH3	338798	549934
	BH4	338823	549896

The samples were cut from core material that was acquired the previous year, and kept, sealed, in cold storage prior to the permeability testing. The original core was from industry-standard U100 samples – approximately 100mm diameter. The cores lengths were logged and photographed prior to sample preparation and care was taken not to disturb the specimens during logging.

Following completion of the permeability tests, the samples were handed over to researchers at the University of Lancaster (via Professor Andrew Binley) for further analysis of geophysical properties.

An additional phase of drilling was carried out by BGS (Tills project) in September 2013 at Hill House Nook in the north of the EdenDTC Pow Catchment. Three boreholes were drilled and the core sealed and later logged and photographed in the BGS laboratories. Permeability tests were carried out on various samples obtained. Data from this second round of tests, carried out in late 2013, are provided in Appendix 2.

2 Test Apparatus

The apparatus configuration is shown in Figure 1. The test apparatus was originally supplied by Wykeham Farrance Eng. Ltd of Slough, Buckinghamshire. However, parts of the equipment proved to be inadequate for a variety of reasons, and as a result the pipe network connecting the cells to the header tank and standpipe tubes was rebuilt using Swagelok fittings and the test cells themselves were modified. These were arranged in such a way as to discourage the entrapment of air bubbles emanating from the test specimen. The central component of the cell is the tightness of fit of the specimen inside the cutter tube. The tube supplied by the manufacturer has an internal diameter of 100mm. This resulted in an immediate problem in that the samples provided were also 100mm in diameter and the normal process of trimming to produce a tight fit in the tube was not possible. Therefore, a plastic liner was fitted to each cell to reduce the internal diameter to a nominal 90mm.

Rubber connecting tubes were replaced with nylon and neoprene tubes and pinch valves replaced with Legris taps. The cell was primed from a header tank supplied with de-ionized, de-aired water. Three capillary standpipes were included in the apparatus, of internal diameter 6mm, 7mm and 10mm. These were supplied in plastic, instead of the traditional glass, and sealed at each end with O-rings. In the past problems have been experienced in dislodging air bubbles (emanating from the test specimen) from the walls of the capillary standpipes, as these adhere more than they would with glass tubes. In this series of tests, no such problems were encountered.

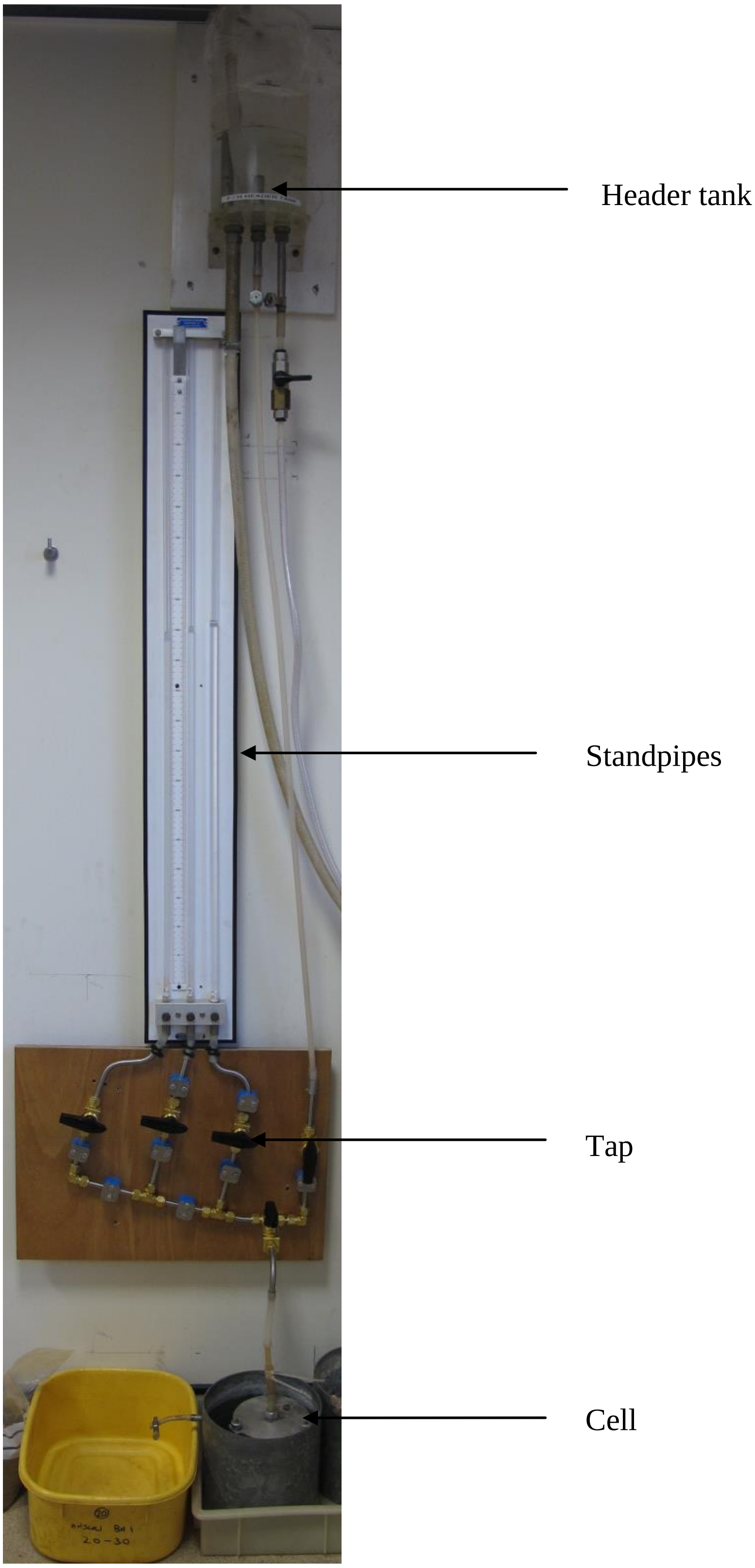

Figure 1: Falling Head Permeability Apparatus

3 Sample Preparation

The plastic sample liner was cut from the sample using a vibrating saw rig at the BGS Core Store labs. This produced less sample disturbance than extrusion of the sample by piston. The plastic

(UPVC) sample tube was then greased on the inside with silicone grease, in order to fill any voids between the sample and the inside of the tube, and weighed. The tube was made from UPVC as this material is non-conductive and could be later retrofitted with electrodes for geophysical work on the sample. A chamfered metal cutting shoe (produced in the BGS workshops) was fitted to the tube to help with the cutting as shown in Figure 2. The sample was trimmed down with a sharp blade as the tube was pushed down over the sample in small increments, using a block of wood to keep the pressure more evenly distributed, to produce a specimen that fitted tightly in the tube (Fig 2). It was essential to produce a tight fit in order to prevent leakage of water between the specimen and the tube.

Figure 2: Trimming the sample to fit the UPVC tube.

In order to fit the tube, a number of gravel-sized clasts had to be removed from most of the samples. The resulting voids were filled with fine-grained material from the sample. The cutting shoe was removed and the ends of the specimen trimmed flat with a straight-edged blade. The specimen and tube were weighed, as well as the excess grease extruded in the process. The specimen was then inserted in a greased metal 100mm diameter cutter tube (from the original test apparatus), and placed in the permeameter cell, as shown in Figure 10.36 in Head (1994). A water tight seal was formed between the cutter tube and UPVC tube by applying silicone (bathroom) sealant to the surfaces and allowing to 'go off' for several hours. The soil sample was immersed in de-ionized, de-aired water and left overnight or longer to saturate and to allow the clay fraction to swell. The cell was placed in a constant level tray with outlet to waste. The height difference between the zero reading on the scale and the overflow level of the tray was measured.

4 Test Method

The connections were made to the cell, and the standpipe tube, interconnecting tubes, and tap primed and de-aired from the header tank. The constant level tray was filled with de-ionized, de-aired water to its overflow level. Water was allowed to flow through the cell and flush out any air remaining in the specimen. When a constant flow had been established the standpipe was primed, the level in the standpipe recorded, and the timer started. The falling levels in the standpipe were recorded at intervals appropriate to each specimen. This varied from seconds to hours, according to the permeability. The temperature of the laboratory was monitored throughout, and remained constant at 20°C.

The method outlined by Head (1994) suggests a single run on the permeameter, with three measurements of Height as the water level falls. But due to the variability of the permeability results, it was decided that a series of measurements would be taken, sometimes over a single run, and in some instances the test was stopped, the standpipes refilled, and another run recorded. The results were recorded as a series of numbered tests, and are displayed as graphs in Figure 3. Each test represents a fall in the water level in the standpipe over a measured time interval (from less than minute to several hours, depending on the permeability). For each sample a series of tests was performed - usually on the same day, but sometimes on subsequent days - and a number of values of permeability obtained. The minimum value of permeability for each sample was quoted in the results table, for reasons described below, in section 7.1.

Errors in the falling head permeability test may arise from the following:

a) Leakage between the test specimen and the sample tube due to leaks in the seal between sample and tube, or between test vessel and tube. Leaks will tend to increase the measured permeability.
b) Incomplete saturation of the test specimen and/or air in the tubing and standpipes. This will tend to decrease the permeability result.
c) The development of fissures in, or swelling of, the specimen, or other changes in the structure of the specimen. This may increase or decrease the measured permeability.
d) Darcy's Law, used to determine the permeability, only applies to laminar flow in a saturated soil and not turbulent flow. However, turbulent flow is unlikely in soils with permeabilities in the region of 10^{-10} to 10^{-9} m/s. Flow in cohesive soils may also be influenced by the nature and content of clay minerals present. This may be strongly time dependent, and influenced by the relative chemistry of the natural pore water and the de-ionized, de-aired water used in the test.
e) Variations in temperature. An increase in temperature will reduce the viscosity of the water and increase the measured permeability.
f) Variation in the diameter of the standpipe.
g) Evaporation of water from the standpipe. This will tend to increase the measured permeability.

5 Calculations

The fundamental equation governing the laminar flow of water through soil is Darcy's Law:

$$Q = A.k.i$$

Where: Q = rate of discharge through a soil of cross-sectional area, A
k = coefficient of permeability
i = hydraulic gradient

This equation only applies to laminar flow through a saturated soil.

The working equation using test data is as follows:

$$K=[a.L / (A.\Delta t)].Log_{10}(h_U / h_L)10^{-5}$$

in which we have:
L: the height of the soil sample column
A: the sample cross section
a: the cross section of the standpipe
Δt: the recorded time for the water column to flow though the sample
h_U and h_L : the upper and lower water level in the standpipe measured using the same water head reference)

6 Test Results

Two hundred and ten falling head permeability tests have been carried out on twenty three samples of glacially derived soil (deformation till). The results for each test are summarised in Table 2 and Table 3, and full test data are saved in W:\Teams\GPP\GeoengPropProcProjMgmt\Data\Geotechnical_Labs\Lab Jobs\201-210\LJ 203 Eden Valley Tills, and summarised in Appendix 1. Temperature corrections to the results were not required due to steady laboratory temperatures (20^{o} Celsius) throughout.

The minimum permeability values range from 1.5 x 10^{-10} m/s to 5.7 x 10^{-5} m/s (Table 2 & 3). The lab samples can be thereby be classified as 'impermeable' to 'medium low' permeability soils and are typical of 'intact clays' to 'fissured and weathered clays' and silts (Head, 1994). Permeability values from samples from the Pow Catchment generally ranged from 10^{-10} to 10^{-5} m/s, whilst values from the Dedra Banks site in the Moorland Catchment showed a slightly narrower range, from 10^{-10} to 10^{-7} m/s, though this is based on two samples. The results show a slight tendency for permeability to increase with depth, although there is no overall relationship between permeability and depth.

Fluctuations in permeability with time are conspicuous in most cases, sometimes varying by as much as one order of magnitude. The majority of these showed a steady decrease in permeability over time, with the notable exception of Sample 5 (from Pow BH3, 3.62-3.75m), which appears to have an exponential-like increase in permeability. This may be due to flushing out of fines during the test or the development of secondary permeability through a fissure. There seems to be no obvious relationship between the permeability of the specimens and the fluctuations in the measured values, although the samples with permeability of more than 10^{-7} m/s do not seem to exhibit this to the same degree as the specimens of very low permeability.

Most of the samples tested are at the lower end of the permeability range recommended for this test (Head, 1994). Permeability testing in the oedometer rather than the falling head cell is recommended for permeabilities of 10^{-9} m/s and less (Head, 1994). However, the oedometer test only accepts a small specimen and is unsuitable for testing tills that contain gravel sized particles. For such materials a large specimen is essential in order to allow as much of the particle size range to be represented as possible, and is more representative of field conditions.

Table 2: Summary of permeability test results for Samples 1-16 from Pow and Moreland Catchments

Sample Number	Site and BH	Sample Depth (m)	Mean Coefficient of Permeability, k (m/s) to 1 decimal	Minimum value, k (m/s)	Standard Deviation (m/s)
1	Pow BH1	0.75-0.93	1.5×10^{-9}	2.8×10^{-10}	1.3×10^{-9}
2	Pow BH1	1.97-2.10	5.2×10^{-9}	3.7×10^{-9}	1.0×10^{-9}
3	Pow BH1	4.84-4.97	9.9×10^{-9}	5.7×10^{-9}	5.0×10^{-9}
4	Pow BH1	7.12-7.25	6.5×10^{-07}	5.7×10^{-7}	6.0×10^{-8}
5	Pow BH3	3.62-3.75	1.1×10^{-09}	3.6×10^{-10}	1.0×10^{-9}
6	Pow BH6	2.80-2.93	3.7×10^{-09}	1.5×10^{-10}	3.3×10^{-10}
7	Pow BH6	1.47-1.60	1.6×10^{-09}	1.2×10^{-9}	3.9×10^{-10}
8	Pow BH1	5.82-5.95	5.0×10^{-08}	1.8×10^{-8}	2.2×10^{-8}
9	Moreland, Dedra Banks BH1	1.47-1.60	1.4×10^{-09}	8.7×10^{-10}	5.6×10^{-10}
10	Moreland, Dedra Banks BH1	1.97-2.10	5.1×10^{-07}	4.2×10^{-7}	4.4×10^{-8}
11	Pow BH2	0.78-0.91	4.9×10^{-06}	2.0×10^{-09}	1.2×10^{-06}
12	Pow BH2	2.03-2.16	2.9×10^{-09}	3.9×10^{-06}	1.5×10^{-09}
13	Pow BH6	0.96-1.09	2.4×10^{-06}	2.3×10^{-06}	1.2×10^{-07}
14	Pow BH7	0.82-0.95	1.1×10^{-05}	1.1×10^{-05}	2.2×10^{-07}
15	Pow BH1	1.20-1.65	1.6×10^{-07}	9.5×10^{-08}	1.0×10^{-07}
16	Pow BH2	1.41-1.54	5.6×10^{-07}	*8.0×10^{-07}	3.5×10^{-07}

*Value used from later tests, which gave higher values of k

Table 3: Summary of permeability test results for Samples 17-23 from Hill House Nook in the north of the Pow Catchment (September 2013 drilling)

Sample Number	Site and BH	Sample depth (m)	Mean Coefficient of Permeability, k (m/s) to 1 decimal	Minimum value, k (m/s)	Standard Deviation (m/s)
17	Pow, Hill House Nook BH2	0.58-0.71	7.8×10^{-06}	4.9×10^{-06}	1.3×10^{-06}
18	Pow, Hill House Nook BH2	1.16-1.33	3.9×10^{-06}	3.1×10^{-06}	5.7×10^{-07}

19	Pow, Hill House Nook BH2	1.70-1.88	4.4×10^{-06}	2.6×10^{-06}	2.4×10^{-06}
20	Pow, Hill House Nook BH2	2.20-2.37	1.3×10^{-08}	5.9×10^{-09}	7.4×10^{-09}
21	Pow, Hill House Nook BH3	1.80-2.00	2.3×10^{-07}	9.0×10^{-10}	2.8×10^{-07}
22	Pow, Hill House Nook BH3	2.38-2.58	1.3×10^{-07}	1.5×10^{-09}	1.0×10^{-07}
23	Pow, Hill House Nook BH4	1.72-1.93	2.0×10^{-07}	4.1×10^{-08}	8.7×10^{-08}

7 Conclusions

Minimum permeabilities for the till samples from the Moreland Catchment and Pow Catchment Eden DTC sites ranged from 8.7 x 10^{-10} m/s to 1.1 x 10^{-5} m/s. The test results appear to be satisfactory.

There is a weak correlation between sample depth and permeability within individual boreholes (see Figure 6). The deepest test sets shows an apparent increase in permeability with depth (e.g. Pow BH1), whereas others show the opposite relationship (e.g. Pow BH2, Hill House Nook BH2). These differences could be due to weathering and soil-forming processes, such as root holes, desiccation cracks, organic content, and inclusion of bedrock (sandy) material towards the base of the deforming later under the ice sheet.

Several tests gave a consistent incremental permeability with time over periods of hours, whilst some were rather variable with time. The reason for this is not clear, as the tests were all subject to the same conditions. One reason could be that the samples did not have time to reach equilibrium; and the clay may still have been expanding (swelling) during the tests, thereby producing a steady decrease in permeability over time. One sample (Pow BH3, 3.62-3.75m) showed an increase in incremental permeability with time.

Due to the very small amounts of water passing through the test specimens, it is usually easy to detect artificial permeability due to leaks. This was observed in some earlier tests, whilst the preparation technique was being developed.

The test method is not ideal, but is a reasonable and cost-effective alternative to permeability testing in the triaxial apparatus. Other methods, such as permeability testing in an oedometer, do not suit the particle size range of this till. All permeability tests involving water stand the risk of air entrapment, both within the test specimen and the tubing, taps, and connectors. One advantage of the triaxial test method is that the test can be conducted at elevated stresses sufficient to enable entrapped air to be taken into solution, and thus not affect permeability.

7.1 NOTES

The bulk density values are subject to minor errors because estimates had to be used for mass of mould + internal grease, due to grease being extruded when sample obtained. In most cases the excess grease was collected and weighed, but it was mixed with some of the till sample. Bulk density and dry density values are reported in Table 6, and plotted against depth in Figure 7, and these are to be treated with due caution.

As noted above, many of the tests show a steady decrease in permeability over time. This suggests that either the clay was still expanding, or there is some error in the parameters used in the calculation of permeability. Assuming that the cause is the expansion (swelling) of the clay, the **minimum** value of permeability should be taken as the most representative value (under fully saturated conditions) for each test.

Taken from Coastal And Engineering Geology and Geophysics Laboratory Report CEGLR99/1C: “It was noted that the hydraulic conductivity reduced as the test proceeded. This was probably due to the sample absorbing water and swelling and to the very low hydraulic conductivity of the material, less than 1x10^{-10} m/s for which the falling head method is not suitable.”

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

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Appendix 1

NB. The graphs below do not have a linear scale for time, the x axis indicates the number of tests taken over various time intervals, sometimes on different days.

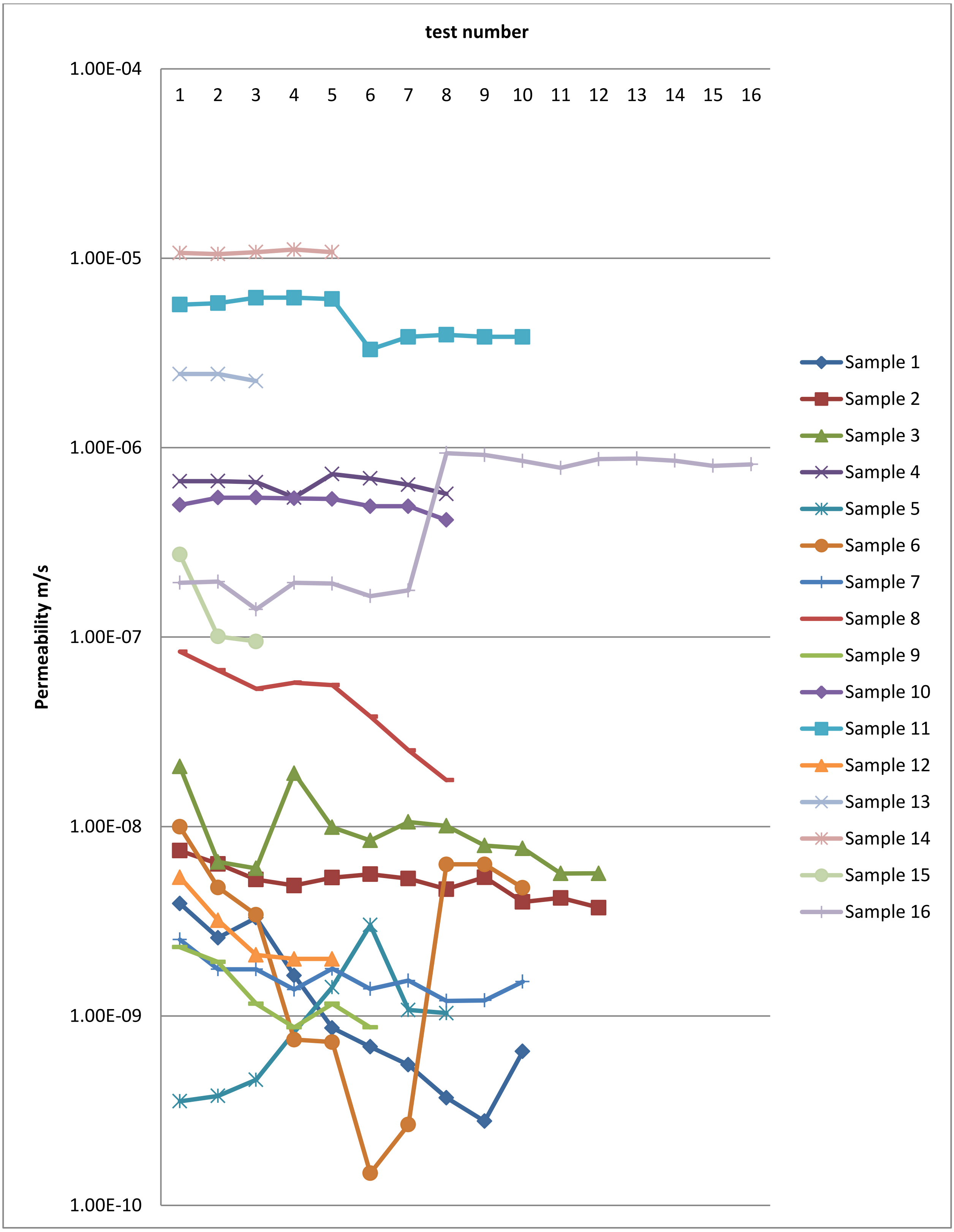

Figure 3: Graph of permeability values for each test carried out on the samples, using data shown in Table 4.

Table 4: Results of permeability tests. Units are m/s (after Morgan et al 2013 with additions).

Test no.	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9	Sample10	Sample11	Sample12	Sample 13	Sample 14	Sample 15	Sample 16
1	3.92E-09	7.46E-09	2.07E-08	6.65E-07	3.55E-10	9.96E-09	2.53E-09	8.38E-08	2.31E-09	4.98E-07	5.70E-06	5.40E-09	2.45E-06	1.07E-05	2.73E-07	1.94E-07
2	2.59E-09	6.35E-09	6.51E-09	6.66E-07	3.78E-10	4.77E-09	1.76E-09	6.68E-08	1.93E-09	5.45E-07	5.80E-06	3.20E-09	2.45E-06	1.05E-05	1.01E-07	1.96E-07
3	3.30E-09	5.25E-09	6.01E-09	6.57E-07	4.60E-10	3.42E-09	1.76E-09	5.33E-08	1.16E-09	5.45E-07	6.20E-06	2.10E-09	2.25E-06	1.08E-05	9.49E-08	1.40E-07
4	1.64E-09	4.88E-09	1.91E-08	5.46E-07	8.19E-10	7.49E-10	1.38E-09	5.75E-08	8.70E-10	5.40E-07	6.20E-06	2.00E-09		1.11E-05		1.94E-07
5	8.64E-10	5.37E-09	9.90E-09	7.26E-07	1.42E-09	7.28E-10	1.78E-09	5.58E-08	1.16E-09	5.36E-07	6.10E-06	2.00E-09		1.08E-05		1.92E-07
6	6.87E-10	5.60E-09	8.45E-09	6.88E-07	3.02E-09	1.48E-10	1.39E-09	3.81E-08	8.70E-10	4.91E-07	3.30E-06					1.65E-07
7	5.52E-10	5.31E-09	1.06E-08	6.38E-07	1.08E-09	2.67E-10	1.54E-09	2.53E-08		4.91E-07	3.85E-06					1.77E-07
8	3.70E-10	4.67E-09	1.01E-08	5.70E-07	1.03E-09	6.31E-09	1.20E-09	1.76E-08		4.15E-07	3.95E-06					9.36E-07
9	2.78E-10	5.40E-09	7.94E-09			6.31E-09	1.21E-09				3.85E-06					9.15E-07
10	6.49E-10	4.00E-09	7.67E-09			4.74E-09	1.52E-09				3.85E-06					8.52E-07
11		4.20E-09	5.65E-09													7.83E-07
12		3.73E-09	5.66E-09													8.71E-07
13																8.77E-07
14																8.55E-07
15																8.02E-07
16																8.17E-07
Mean (m/s)	1.48E-09	5.18E-09	9.86E-09	6.45E-07	1.08E-09	3.74E-09	1.61E-09	4.98E-08	1.38E-09	5.08E-07	4.88E-06	2.94E-09	2.38E-06	1.08E-05	1.56E-07	5.60E-07
Std dev	1.32E-09	1.03E-09	5.02E-09	5.96E-08	1.03E-09	3.28E-09	3.90E-10	2.18E-08	5.95E-10	4.43E-08	1.20E-06	1.47E-09	1.15E-07	2.22E-07	1.01E-07	3.49E-07
Min value (m/s)	2.78E-10	3.73E-09	5.65E-09	5.70E-07	3.55E-10	1.48E-10	1.20E-09	1.76E-08	8.70E-10	4.15E-07	3.30E-06	2.00E-09	2.25E-06	1.05E-05	9.49E-08	7.83E-07
Bulk density (Mg/m3)	1.95	2.18	2.27	2.23	2.25	1.93	1.94	2.28	2.25	2.22	2.13	2.26	2.12	1.95	2.22	2.19
Dry Density (Mg/m3)	1.65	1.92	2.08	2.02	2.08	1.78	1.71	2.13	2.02	1.95	1.88	2.03	1.87	1.52	2.00	1.96

Appendix 2 September 2013 test data (Pow Catchment)

Table 5: Results of permeability tests for September 2013 data. Units are m/s.

Test No.	Sample 17	Sample 18	Sample 19	Sample 20	Sample 21	Sample 22	Sample 23
1	5.66E-06	4.16E-06	8.49E-06	2.55E-08	6.39E-07	1.88E-07	2.16E-07
2	5.77E-06	4.29E-06	8.58E-06	1.38E-08	5.38E-07	9.96E-08	2.03E-07
3	4.88E-06	4.58E-06	4.58E-06	1.03E-08	4.80E-07	1.88E-07	2.30E-07
4	7.72E-06	4.16E-06	3.23E-06	1.10E-08	4.05E-07	1.75E-07	2.28E-07
5	7.70E-06	4.45E-06	3.32E-06	5.92E-09	3.12E-09	2.58E-07	6.48E-08
6	7.67E-06	4.65E-06	3.06E-06		1.96E-09	2.42E-07	4.07E-08
7	8.27E-06	4.00E-06	2.64E-06		1.67E-09	2.34E-07	1.33E-07
8	9.00E-06	4.29E-06	2.74E-06		1.33E-09	1.62E-07	3.04E-07
9	8.71E-06	4.44E-06	2.88E-06		9.00E-10	3.15E-09	2.43E-07
10	8.33E-06	3.14E-06				2.44E-09	2.68E-07
11	7.55E-06	3.15E-06				1.99E-09	2.92E-07
12	9.38E-06	3.34E-06				1.52E-09	
13	8.58E-06	3.18E-06					
14	8.69E-06	3.32E-06					
15	8.71E-06	3.38E-06					
Mean (m/s)	7.77E-06	3.90E-06	4.39E-06	1.33E-08	2.30E-07	1.30E-07	2.02E-07
Std dev	1.33E-06	5.76E-07	2.42E-06	7.38E-09	2.77E-07	1.03E-07	8.70E-08
Min Value (m/s)	4.88E-06	3.14E-06	2.64E-06	5.92E-09	9.00E-10	1.52E-09	4.07E-08
Bulk density (Mg/m3)	2.14	2.14	2.02	2.29	2.19	2.19	2.19
Dry Density (Mg/m3)	1.71	1.91	1.74	2.12	1.97	1.99	1.95

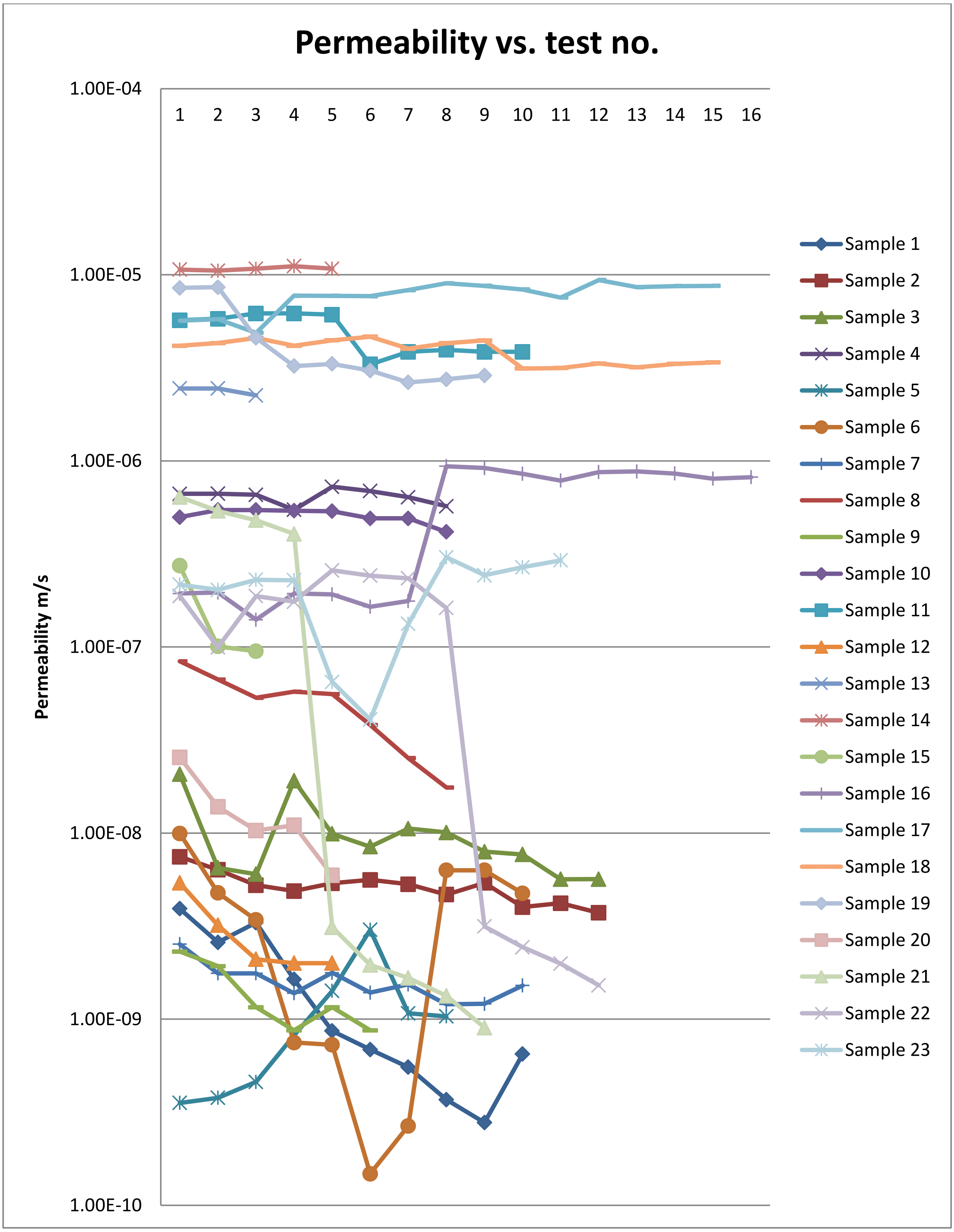

Figure 4: Compilation graph including new data from Table 4 and Table 5

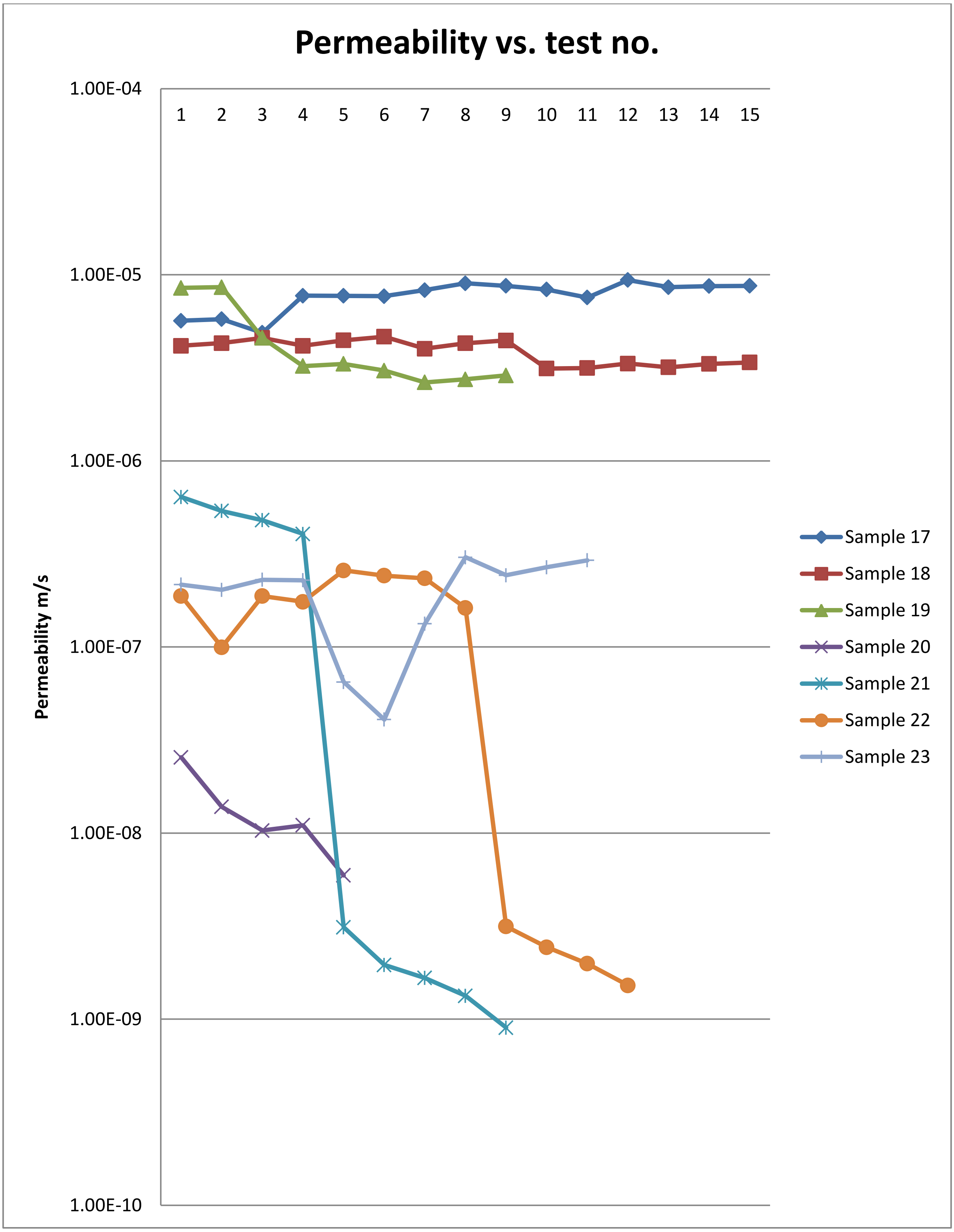

Figure 5: Compilation graph of Pow Catchment (Hill House Nook BHs) 2013 data only

Notable features of the new 2013 data:

- The results have a range of values similar to the first round of tests: from 10^{-09} to 10^{-6} m/s
- Three samples showing relatively high hydraulic conductivities: samples 17, 18 and 19. These all have conductivities in the range 2.6 x 10^{-6} m/s to 4.9 x 10^{-6} m/s. All were taken from the top 2m of Borehole 2.
- The wide range of results for samples 21 and 22. The lower values here were obtained several days after the first batch of tests after refitting the cells in their plastic liners into the metal test cells, and running the tests again. The different results could be explained by some degree of resorting of the sediment within the cell, or leakage of water between the plastic liner and metal cylinder during the test.
- The same repeat test was done for sample 17, which produced results similar to the earlier runs. However, a repeat test of sample 23 gave values an order of magnitude higher. Perhaps some degree of resorting of the matrix opened up pathways allowing greater flow of water through the sample.

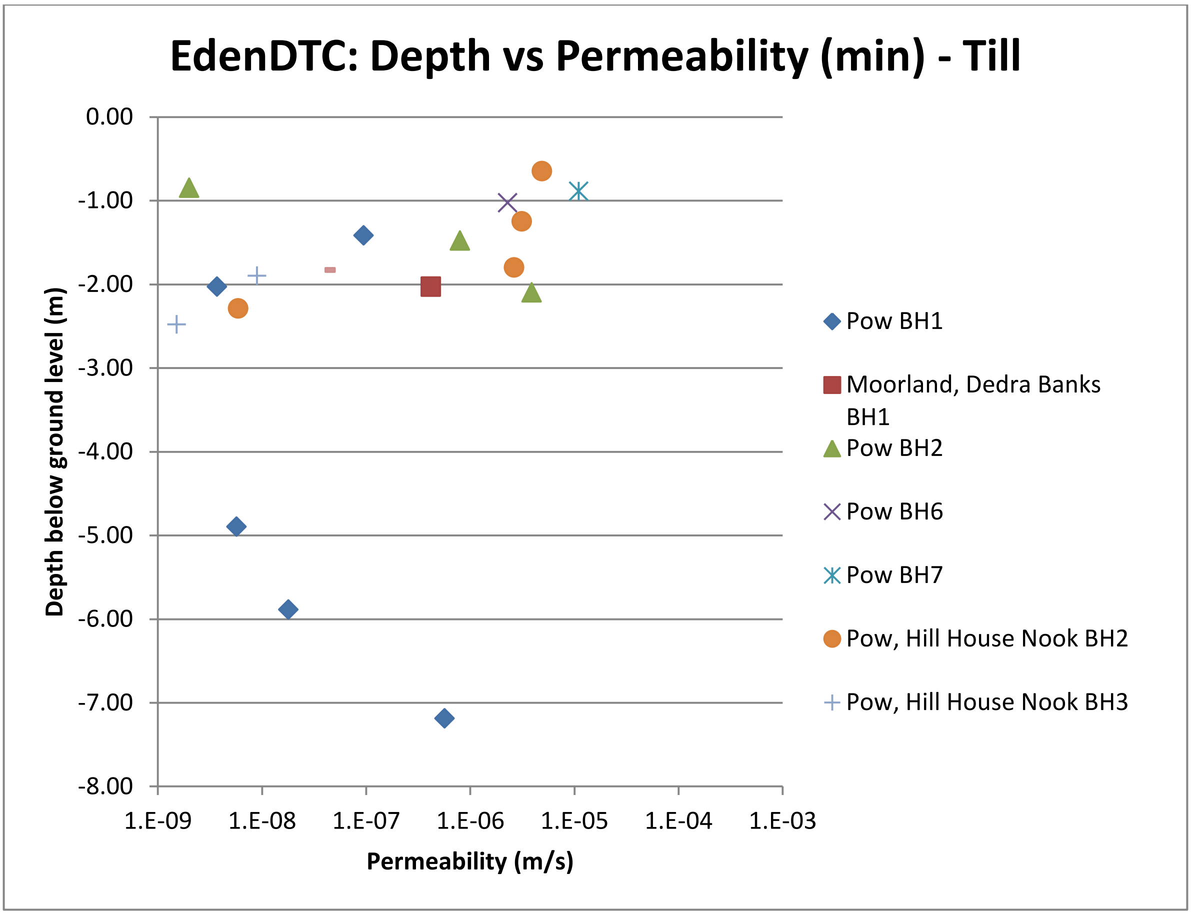

Figure 6: Plot of 'minimum' lab permeability values against depth (centre point of sample).

Density

Table 6: Density values and sample descriptions

Sample No.	Site and BH	Bulk Density (Mg/m^3)	Dry Density (Mg/m^3)	Description
1	Pow BH1	1.95	1.65	Soft to firm mottled yellowish red and pale brown gravelly sandy CLAY becoming clayey SAND at base, with extremely closely spaced rootlets. Gravel is fine to coarse rounded to well-rounded. TILL
2	Pow BH1	2.18	1.92	Dark brown slightly gravelly clayey fine SAND with 1cm wide vertical vein of grey, gleyed sand through centre. TILL
3	Pow BH1	2.27	2.08	Stiff dusky red (10R 3/4) gravelly very sandy CLAY. Sand mainly fine. Gravel fine to coarse subrounded to well rounded, mixed lithology, including highly weathered dark green basalt. Calcareous. Sand content increases with depth. Organic remains (oak leaf?) found between core and liner at 5.00m. TILL.
4	Pow BH1	2.23	2.02	Hard dark red (2.5YR 3/6), becoming reddish brown (2.5YR 4/4) below 6.95, gravelly clayey SAND. Sand fine to coarse, gravel fine to medium, subrounded to well rounded, mixed lithology. Calcareous. TILL.
5	Pow BH3	2.25	2.08	Firm dark reddish brown gravelly very sandy CLAY. Becoming less sandy towards base. Sand fine to coarse. Gravel fine to coarse, subrounded to well rounded, mixed lithology. Calcareous. TILL.
6	Pow BH6	1.93	1.78	Hard reddish brown gravelly very sandy CLAY (Till)
7	Pow BH6	1.94	1.71	Firm to stiff reddish brown gravelly sandy CLAY (Till)
8	Pow BH1	2.28	2.13	Hard dusky red gravelly clayey SAND (Till)
9	Moorland, Dedra Banks BH1	2.25	2.02	Stiff dark greyish brown gravelly sandy CLAY (Till)
10	Moorland, Dedra Banks BH1	2.22	1.95	Firm dark greyish brown gravelly sandy CLAY (Till)
11	Pow BH2	2.13	1.88	Medium dense reddish brown gravelly silty/clayey SAND. TILL
12	Pow BH2	2.26	2.03	Firm reddish brown gravelly clayey SAND. TILL.
13	Pow BH6	2.12	1.87	Firm to stiff reddish brown gravelly very sandy CLAY. TILL
14	Pow BH7	1.95	1.52	Firm reddish brown gravelly clayey SAND (remoulded?). TILL
15	Pow BH1	2.22	2.00	Hard reddish brown gravelly clayey SAND with gleyed silty fine sand-filled sub-vertical fracture down middle of sample. TILL
16	Pow BH2	2.19	1.96	Hard reddish brown gravelly clayey SAND. TILL.
17	Pow, Hill House Nook BH2	2.14	1.71	Stiff reddish brown slightly gravelly very sandy CLAY. TILL
18	Pow, Hill House Nook BH2	2.14	1.91	Stiff reddish brown slightly gravelly very sandy CLAY. TILL
19	Pow, Hill House Nook BH2	2.02	1.74	Stiff reddish brown gravelly very sandy CLAY. Part of sample very soft. TILL
20	Pow, Hill House Nook BH2	2.29	2.12	Hard reddish brown cobbly very gravelly very sandy CLAY. Fissured; voids. TILL
21	Pow, Hill House Nook BH3	2.19	1.97	Stiff reddish brown cobbly gravelly very sandy CLAY. TILL
22	Pow, Hill House Nook BH3	2.19	1.99	Very stiff reddish brown cobbly gravelly very sandy CLAY. TILL
23	Pow, Hill House Nook BH4	2.19	1.95	Stiff/very stiff yellowish red cobbly very gravelly very sandy CLAY. TILL

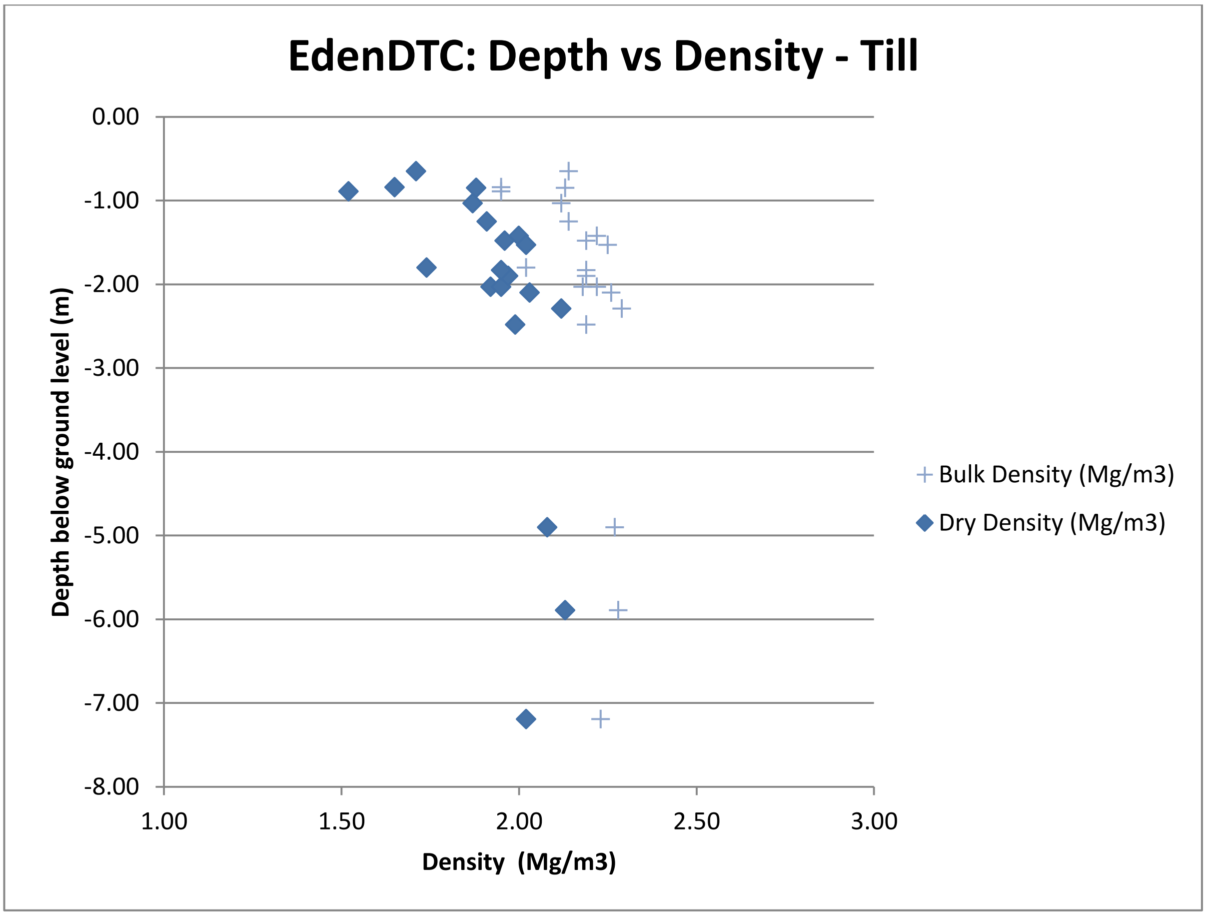

Figure 7: Plot of till density against depth