

# 1 Relating *in situ* hydraulic conductivity, particle size and relative 2 density of superficial deposits in a heterogeneous catchment

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## 11 Abstract

12 Estimating the permeability of superficial deposits is fundamental to many aspects of catchment  
13 science, but can be problematic where insufficient *in situ* measurements are available from pumping  
14 tests in piezometers. Consequently, common practice is to estimate permeability from the material  
15 description or, where available, particle size distribution using a formula such as Hazen. In this  
16 study, we examine the relationships between particle size, relative density and hydraulic  
17 conductivity in superficial deposits in Morayshire, Northern Scotland: a heterogeneous environment  
18 typical of many catchments subject to previous glaciations. The superficial deposits comprise  
19 glaciofluvial sands and gravels, glacial tills and moraines, raised marine sediments, and blown sands.  
20 Thirty-eight sites were investigated: hydraulic conductivity measurements were made using  
21 repeated Guelph Permeameter measurements, cone resistance was measured *in situ* with a Panda  
22 dynamic cone penetrometer; material descriptions were made in accordance with BS5930:1999; and  
23 disturbed samples were taken for particle size analysis. Overall hydraulic conductivity (K) varied  
24 from 0.001 m/d to > 40 m/d; glacial till had the lowest K (median 0.027 m/d) and glacial moraine the  
25 highest K (median 30 m/d). However, within each geological unit there was great variability in  
26 measured hydraulic conductivity values. Multiple Linear regression of the data indicated that  $\log d_{10}$

27 and relative density (indicated by cone resistance or BS5930:1999 soil state description) were  
28 independent predictors of log K and together gave a relationship with an  $R^2$  of 0.80. Material  
29 description using the largest fraction (e.g. sand or gravel) had little predictive power. Therefore, in  
30 heterogeneous catchments, the permeability of superficial deposits is most strongly related to the  
31 finest fraction ( $d_{10}$ ) and relative density of the material. *In situ* Guelph permeameter  
32 measurements at outcrops with good geological characterisation provide an easy and reliable  
33 method of determining the permeability of particular units of superficial deposits.

34 *Keywords: Permeability; Superficial deposits, Particle Size, Permeameter, Relative density, Hydraulic*  
35 *conductivity*

36

## 37 1. Introduction

38 Estimating the permeability of superficial deposits is fundamental to many aspects of catchment  
39 science and hydrogeology. It is critical to characterising groundwater/surface water interaction and  
40 in particular baseflow to upland rivers (e.g. Morrice et al., 1997; Soulsby et al., 2007); groundwater  
41 vulnerability assessments (Gogu RC and Dassargues 2000; Lake et al., 2003; Ó Dochartaigh et al.,  
42 2005); urban hydrogeology (Bruce and McMahon, 1996; Chilton, 1999); groundwater recharge  
43 (Lloyd et al., 1981; Cuthbert et al., 2009; Misstear et al. 2009; Griffiths et al., 2011) and increasingly  
44 for predicting and mitigating flooding (Macdonald et al., 2008). Where sufficiently permeable and  
45 saturated, superficial deposits form aquifers which can be developed for both private and public  
46 water supply (e.g. Maupin and Barber, 2005; MacDonald et al., 2005).

47 The most obvious, and reliable, way to estimate permeability is through testing the saturated  
48 portion of the aquifer using constant rate pumping tests in piezometers (e.g. Melville et al., 1991;  
49 Jones et al., 1992; Jones, 1993; Meinken and Stobar, 2003). However, there are a number of  
50 difficulties in relying solely on piezometers for characterising the permeability of superficial deposits:  
51 (1) superficial deposits are highly complex, and sufficient boreholes are not generally available for  
52 testing; (2) the deposits are often unsaturated (pumping tests are only applicable below the water-  
53 table); (3) permeability can be too low to measure easily with standard pumping tests (Jones, 1993;  
54 Renard, 2005); (4) the complexity of superficial sequences can mean that it is difficult to control  
55 which units are being tested, and (5) fine-grained material can smear borehole walls causing  
56 permeability to be underestimated (McKay et al., 1993). Various methods have been designed to  
57 directly measure *in situ* permeability within soil, for example disc permeameters and infiltrometers  
58 (Perroux and White, 1988; Angulo-Jaramillo et al., 2000), constant head permeameter (Amoozegar  
59 1989; Elrick et al. 1989); but these methods are rarely used below the top soil.

60 Therefore, due to a lack of directly measured permeability data , surrogate information is used – for  
61 example particle size analysis (e.g. Song et al., 2009), or permeability is inferred from the geological  
62 description (e.g. McCloskey and Finnemore, 1996; Fogg et al., 1998; McMillan et al., 2000). The  
63 relationship between permeability and particle size is well established and has been used as a  
64 predictive tool since the 19<sup>th</sup> century (e.g. Hazen, 1892; Schlichter, 1899). These relationships are  
65 still used today, and in a review of 19 studies of particle size and permeability Shepherd (1989)  
66 demonstrated the clear trend of increasing permeability with increasing particle size.  $D_{10}$  (the  
67 particle diameter that 10 % of the sample is finer than) is often seen as the best predictor of  
68 permeability and central to many formulae used for calculating permeability (e.g. Hazen, 1892;  
69 Kozeny, 1927; later modified by Carman, 1937, Carrier, 2003). However, many different methods  
70 predict permeability using particle size data. For example, Alyamani and Şen (1993) used the full  
71 distribution of particle sizes, rather than just the  $D_{10}$ ; and Cronican and Gribb (2004) developed a  
72 method of determining permeability from particle size information in materials containing more  
73 than 70 % sand. Permeability values derived from particle size analysis are different depending upon  
74 which formulae are used (Vuković and Soro, 1992; Milham and Howes, 1995; Odong, 2007; Song et  
75 al., 2009; Vienken and Dietrich, 2011). It is generally agreed that determining permeability using  
76 particle size analysis is best suited to loose sand and gravel dominated sediments and is less suited  
77 to deposits dominated by silt and clay (Vokovic and Soro, 1992; Chapuis, 2004).

78 It is clear that particle size alone does not determine permeability, and the wider factors controlling  
79 permeability are the subject of ongoing study. Permeability of unconsolidated deposits is affected  
80 by the particle shape, particle packing and degree of compaction (e.g. Sperry and Peirce, 1995;  
81 Koltermann and Gorelick, 1995). Permeability is much higher in loose sediments than in compact  
82 (dense) sediments, which have lower porosity and a less well developed network of interconnected  
83 voids (Summers and Weber, 1984; Taylor et al., 1990; Koltermann and Gorelick, 1995; Watabe et al.,  
84 2000; Hubbard and Maltman, 2000; Mondol et al., 2007). These complicating factors are more

85 significant in heterogeneous material, where the clay content, compaction and deformation of the  
86 deposits are variable. In many catchments, and in particular those that have been subject to  
87 glaciation, superficial deposits are highly heterogeneous and therefore it is often not appropriate to  
88 use standard particle size models to reliably predict permeability.

89 Scale effects, and ensuring that permeability measurements relate to the same material that  
90 engineering data (e.g. particle size analysis, relative density) have been collected for, provide  
91 additional problems for developing robust models. Removing material to carry out permeability  
92 measurements in a laboratory allows good control over the material on which the tests are being  
93 carried out, but compromises the *in situ* characteristics of packing and density. Removing the  
94 material as a core can partially overcome these issues, but the material needs very careful handling  
95 to avoid deformation; also if the material is taken as a core then normally only vertical permeability  
96 can be measured, and thus be limited by the lowest permeability layer within the sequence. *In situ*  
97 tests such as pumping tests or slug tests sample a larger area and often report higher permeabilities  
98 than laboratory tests, mainly due to the presence of fracturing (Daniel, 1989; Neuzil, 1994; Schulze-  
99 Makuch et al., 1999; Gierczak et al., 2006). This is particularly common within very low permeability  
100 till material (e.g. Hendry, 1982; Keller et al., 1988; Fredericia, 1990; McKay et al., 1993; Nilsson et al.,  
101 2001). If tills are not fractured, then scale effects are less of an issue (Keller et al., 1989).

102 In this study, we examine a variety of superficial deposits from Morayshire, Northern Scotland,  
103 measuring *in situ* saturated hydraulic conductivity, taking samples for particle size analysis, making  
104 soil descriptions, and measuring *in situ* cone resistance. The aim is to examine the relationships  
105 between particle size, relative density and hydraulic conductivity, and to determine how well the  
106 surrogate data predict hydraulic conductivity in this heterogeneous suite of deposits, typical of many  
107 catchments that were subject to Quaternary glaciations.

108

## 109 2. Study area

110 The northeast coast of Scotland, between Inverness and Aberdeen, has interesting hydrology and  
111 geology, which have a significant impact on land use and society. Several major rivers flow  
112 northward from the Grampian highlands in the south towards the Moray Firth (Figure 1). These  
113 rivers are prone to flooding (McEwen and Werrity, 2007), and considerable effort and resource is  
114 being invested in developing flood alleviation schemes to protect the coastal towns of Elgin and  
115 Forres. Previous glaciation of this area has resulted in the formation of a coastal strip of flat land  
116 approximately 10 – 20 km wide. This ground is underlain by 10s of metres of superficial deposits  
117 which form fertile soils and enable high-value agriculture. The coastal strip receives relatively little  
118 rainfall compared to the rest of Scotland (< 600mm) and groundwater is widely abstracted for  
119 agricultural and industrial use, and in some locations for public supply (Ó Dochartaigh et al., 2010).  
120 Characterising the permeability of the strata is fundamental to helping to predict and mitigate  
121 flooding, assess the risk of groundwater flooding, and also assess the potential of the superficial  
122 materials for sustaining large scale groundwater abstraction.

123 The area is underlain by a complex succession of Glacial and Post Glacial strata (Figure 1) that have  
124 mainly accumulated during the last 25,000 years. These range in thickness from a few to many tens  
125 of metres. The sandstone and ancient crystalline bedrock is generally concealed beneath a variable  
126 thickness of glacial till (Figure 1 and 2). Much of this till was laid down during the Main Late  
127 Devensian ice-sheet glaciation of Scotland, although some sandy tills and associated moraines in the  
128 coastal area were deposited by re-advances of a major fast-flowing glacier that occupied the Moray  
129 Firth after the surrounding uplands had become ice free. Most of the glacial tills crop out in steep  
130 river cliffs, where they are seen to be overlain by a considerable thickness of sand and gravel that  
131 were deposited by glacial meltwaters as the ice decayed. Mounds and ridges of poorly sorted  
132 cobble and boulder gravel were laid down in contact with the ice, whereas the well stratified sand

133 and gravel that forms terraces up to 15 m in height on the flanks of the present valleys were  
134 deposited by meltwater rivers beyond the ice margins. In the coastal area meltwater flowed into  
135 what is now the Inner Moray Firth, where it mixed with seawater and laid down sandy and silty  
136 glaciomarine sediments many metres in thickness.

137 Much of the outcrop of the glacial, glaciofluvial and glaciomarine deposits is concealed by Post  
138 Glacial sediments (Figure 2). Along the coast, the glaciomarine sediments are largely buried beneath  
139 Post Glacial raised shoreline deposits of silt and sand, and both are locally concealed beneath  
140 extensive dunes of blown sand. Inland glacial, glaciolacustrine and glaciofluvial sediments have been  
141 reworked by rivers and streams to form spreads of sandy and gravelly alluvium and river terraces  
142 along the major valleys; silty lacustrine deposits and peat infill many ice scoured hollows and  
143 kettleholes, and blanket peat is still accumulating on the higher ground.

144

### 145 **3. Methods**

#### 146 **3.1 General/Site selection**

147 Twenty-five sections of superficial deposits for which the geology is well characterised were selected  
148 in an area of approximately 250 km<sup>2</sup> (Figure 1). The sites were chosen to include all the main types  
149 of superficial deposits present. Sections were between 2 and 20 m high, and at some sections  
150 several different types of superficial deposits were present and were sampled. Figure 3 shows a  
151 photograph of a typical section. In total, 38 different deposits were sampled at the 25 sections of  
152 which 14 were glacial tills, 3 were glacial moraines, 7 were glaciofluvial sands and gravels, 3 were  
153 glaciolacustrine deposits, 8 were raised marine deposits, and 3 were blown sand deposits.

154 Each site was visited by a team including a Quaternary geologist, hydrogeologist and engineering  
155 geologist. The Guelph permeameter was used to obtain an *in situ* measurement of the hydraulic

156 conductivity of the deposits. The cone resistance of the material was measured *in situ* with a Panda  
157 dynamic cone penetrometer to give an indication of relative density, superficial deposit descriptions  
158 were made at the outcrop in accordance with BS5930:1999 (British Standards Institute, 1999a); and  
159 disturbed samples were taken for particle size analysis. At each site, *in situ* Guelph permeameter  
160 and Panda cone penetrometer measurements were carried at the same place within the outcrop  
161 and within the same material, which was then sampled for particle size analysis.

### 162 **3.2 Guelph permeameter field methods**

163 The Guelph permeameter measures the field saturated hydraulic conductivity of unsaturated  
164 deposits and involves measuring the volume of water required to maintain a steady-state constant  
165 head using a Mariotte bottle system constructed of plastic tubes (Figures 3 and 4, see Reynolds and  
166 Elrick (1985) for a full description of the apparatus and procedure). The major advantage of this type  
167 of test is that the material is *in situ* so a more representative volume of material can be tested than  
168 in the laboratory (Daniel, 1989). In this study, the one head method was used (Elrick et al., 1989;  
169 Reynolds et al., 1992) which should generally give results within 25% of the two head method. The  
170 permeameter used has an approximate quoted range of  $10^{-7}$  to  $10^{-4}$  m/s; however we found the  
171 permeameter to have repeatable results slightly outside this range and determined a practical range  
172 of 0.001 to 40 m/d ( $1.2 \times 10^{-8}$  to  $5 \times 10^{-4}$  m/s). Others have also used the Guelph permeameter  
173 within this expanded range (e.g. Lee et al., 1985; Mohanty et al., 1995).

174 Six sections were sampled in September 2008 and the remaining sections were sampled in June  
175 2009. At each measuring point a flat ledge was excavated into the exposure at least one metre  
176 below the soil (Figures 3 and 4). The ledge extended into the face ensuring that measurements were  
177 not affected by small scale fracturing at the edge of the ledge, or by the roots of any vegetation  
178 present at the top of the outcrop. A hole of constant diameter (which ranged from 5 to 6 cm  
179 between test sites) with a depth of 6 to 10 cm was excavated into the ledge. In clayey materials the



180 walls were de-smearred using a sharp metal spoon and small wire brush (Bagarello et al., 1997). The  
181 Guelph Permeameter was placed in the hole immediately after excavation with a small pack of 5 –  
182 10 mm pea gravel to prevent the sides of the hole collapsing. Water was released from the Guelph  
183 Permeameter to obtain a constant head of 4 to 5 cm in the hole. Gradations on the Guelph  
184 Permeameter were read at regular intervals to determine the rate of water input required to  
185 maintain the head. Readings were taken at intervals determined by the rate of water movement  
186 and varied from every 5 seconds to every 15 minutes depending upon the permeability of the  
187 deposit. In the highest permeability deposits measurements were made until the reservoir emptied,  
188 but in other deposits measurements continued until a regular rate of water input was consistently  
189 observed.

190 At most sampling locations a second measurement was made in the same deposit, and if there were  
191 substantial variations between the two measurements or some other problem (e.g. flooding,  
192 collapse, or cracking of the material surrounding the hole), a third measurement was made. The  
193 repeated measurements were made on a new ledge constructed at the same depth and into the  
194 same material as the first. Occasionally it was only possible to obtain one reliable measurement in a  
195 deposit type because of the geometry of the section, or because the permeability was below the  
196 measuring capacity of the permeameter. Hydraulic conductivity was calculated from the data using  
197 the software G-Perm1 which is based on the formulae outlined in Reynolds and Elrick (1985).

### 198 **3.3 Soil description field method**

199 Soil descriptions, in accordance with British Standards BS5930:1999 (British Standards Institution  
200 1999a) and BS5930:1999 amendment 1 (British Standards Institution, 1999b), were made for all the  
201 superficial deposits encountered at each section by an engineering geologist. The standards  
202 systematically describe the state, structure, colour and the size and relative proportions of  
203 composite particles. Particular emphasis was given to the descriptions of *soil state* which directly

204 describes relative density (for coarse soils) or is directly related to relative density (for fine soils).  
205 Descriptions of fine soils were made in accordance with BS5930:1999 amendment 1 such that the  
206 *soil state* of silt and clay was described from very soft through soft, firm and stiff to very stiff.  
207 Descriptions of coarse soils were made in accordance with BS5930:1999 such that the *soil state* of  
208 sand and gravel was described from very loose through loose, medium dense, dense to very dense.  
209 Descriptions of all soil properties were based solely on field observation.

210 In order to allow the relationship between soil *state* and hydraulic conductivity to be quantified a  
211 Soil State Description Value (SSD) was derived. The coarse *soil state* descriptions were numerically  
212 ranked from 1 to 5, very loose to very dense. The *soil state* descriptions for fine deposits were  
213 numerically ranked from 1 to 5 from very soft to very stiff.

214

#### 215 **3.4 Particle size distribution sampling and analysis**

216 Large disturbed bulk samples were taken from each superficial deposit, at each location, in  
217 accordance with BS5930:1999 amendment 1 (British Standards Institution, 1999b). Large cobbles  
218 and boulders were not sampled due to limitations on the mass of material that could be obtained at  
219 each outcrop. Instead, a note of any omission of large cobbles and boulders was made for each  
220 sample where it occurred, and the mass percentage of cobbles and boulders was estimated and  
221 added to the soil description. The particle size distribution analysis data does not include particles  
222 larger than cobble size (>200 mm). The sample material was obtained adjacent to *in situ* test  
223 locations to ensure they were representative of the deposits tested by both the Guelph  
224 permeameter and Panda penetrometer.

225 Thirty-four samples were tested for particle size distribution in accordance with BS1377:Part 2:1990  
226 (British Standards Institution, 1990) and Eurocode 7: Part 2 (2007). The analysis was undertaken  
227 using the wet sieving method. Where a significant fraction (>10%) of material <63  $\mu\text{m}$  remained,

228 further analysis was undertaken to separate the silt and clay fraction. Fine particle analysis was  
229 undertaken, in accordance with Eurocode 7 (2007), by x-ray monitored gravity sedimentation using a  
230 Micromeritics SediGraph III. As part of the analysis the  $d_{10}$ ,  $d_{15}$ ,  $d_{30}$  and  $d_{60}$  for each sample was  
231 calculated, corresponding respectively to the 10<sup>th</sup>, 15<sup>th</sup>, 30<sup>th</sup> and 60<sup>th</sup> percentile of the particle size  
232 distribution.

233

### 234 3.5 Panda penetrometer field methods

235 Dynamic cone penetrometer measurements were undertaken for thirty deposits at 23 locations. This  
236 technique measures the *in situ* dynamic cone resistance (in megapascals - MPa) of the soil through  
237 which the cone is passing and is, therefore, directly related to the relative density of the deposit. The  
238 test was undertaken by driving a 4 cm<sup>2</sup> steel cone on the end of a set of 0.5 m long threaded steel  
239 rods through the target deposit using a fixed weight hammer. The Panda2 measures the velocity of  
240 the hammer impact on the head of the rods and the depth of cone penetration in order to  
241 determine the dynamic cone resistance using a modified form of the Dutch Formula (Langton, 1999).  
242 The method can reach depths of up to 6 m in soils with a resistance up to 20 MPa. It is relatively  
243 lightweight (20 kg) and portable thereby making it ideal for testing soils *in situ*. A more detailed  
244 explanation of the Panda Penetrometer testing methodology and correlations with other dynamic  
245 and static cone penetration tests can be found in Langton (1999).

246 The thirty *in situ* Panda Penetrometer tests were carried out in two field seasons: Sept/Oct 2008 and  
247 June 2009. The tests were undertaken adjacent to the location of the Guelph permeameter tests to  
248 ensure the deposits tested were representative of those tested by the Guelph permeameter.  
249 However, tests were performed sufficiently far apart (in the order of 1 – 5 m), in order to minimise  
250 the interference effects. Panda penetrometer tests were also not performed at the same time as  
251 Guelph permeameter so that vibration did not affect deposits being tested by the Guelph

252 permeameter. At each location an initial attempt was made to test the entire exposed section by  
253 probing from the top of the section to the base. Where this was not possible then a flat shelf or  
254 series of shelves were dug at appropriate intervals so as to intersect the target strata (Figure 5). The  
255 test was terminated once effective refusal was reached (where cone resistance was consistently >20  
256 MPa) or once the rod length was below the level of the exposed section. Where effective refusal  
257 occurred as the likely result of an isolated obstacle, such as a cobble or boulder, then a repeat test  
258 was conducted at the same level but offset by a few metres to avoid the obstacle. Where refusal  
259 occurred in dense and/or cobbly and bouldery strata (i.e. where obstacles were not isolated) then a  
260 second test was undertaken, where possible, on a flat excavated shelf or surface below the level of  
261 the dense and/or coarse stratum.

262 The dynamic cone resistance measured at each test location was recorded by the Panda2 unit as a  
263 single sounding. Examples of typical soundings from two sites are shown in Figure 6. There is  
264 variability in the dynamic cone resistance measured by each separate hammer blow, which is to be  
265 expected in heterogeneous deposits. However, it is possible to correlate sections of the Panda  
266 sounding with separate layers identified as part of the geological descriptions made in the field. The  
267 median value of the section referring to the target geological unit was used in the analysis. Where  
268 more than one Panda test was undertaken in a deposit, the average was used.

## 269 **4. Results**

### 270 **4.1 Guelph permeameter results**

271 The field data produced consistent plots of water-level through time indicating the steady infiltration  
272 rate of water during the test required for analysis (Figure 7). Figure 8 shows that repeat samples in  
273 the same deposit type at the same outcrop give similar hydraulic conductivity ( $R^2 = 0.9$ ) indicating  
274 that the measurements are reproducible. For the 28 sample sites where 2 or more reliable hydraulic  
275 conductivity values were obtained, a mean hydraulic conductivity for the site was used for further

276 analysis. Since Figure 8 indicates a high degree of reproducibility in the data, the 10 sampling sites  
277 for which only one measurement could be made were also used in the further data analysis  
278 described below.

279 The results for the 38 sampling sites are presented in Table 1 and Figure 9. Hydraulic conductivity is  
280 highly variable within, as well as between, particular types of superficial deposits from different  
281 sample locations reflecting the heterogeneity of these types of materials. Glacial tills had the lowest  
282 hydraulic conductivity with a median of 0.027 m/d, but a range of < 0.001 m/d to approximately 1  
283 m/d. Glacial fluvial deposits, (comprising both fluvial and lacustrine deposits) had a much higher  
284 hydraulic conductivity with a median of 2.5 m/d, but again a wide range, < 0.1 to > 40 m/d. The  
285 raised marine deposits showed fairly consistent hydraulic conductivity with median 1.7 m/d and  
286 interquartile range of 0.9 – 3 m/d. Raised Marine deposits in this area are variable in composition  
287 and include sands and gravels with relatively high permeability, and the Ardersier Silt Formation  
288 which varies in composition from sands to silts. Two sites were in the raised marine Ardersier Silt  
289 Formation where it is predominantly silt and these had lower permeability than other sites in Raised  
290 Marine deposits. There were few sites in blown sand and glacial moraines. The three available  
291 blown sand results were consistent and varied from 4.5 to 9.5 m/d reflecting the uniform nature of  
292 the material. The three sites testing glacial moraine deposits showed variable permeability 0.15 to >  
293 40 m/d, and one site had the highest permeability recorded in Morayshire, exceeding the measuring  
294 capacity of the Guelph permeameter.

#### 295 **4.2 Engineering data**

296 Summary graphs displaying particle size distribution analysis envelopes for each superficial deposit  
297 are presented in Figure 10. The  $d_{10}$ ,  $d_{60}$  and sample descriptions are given in Table 1. The graphs  
298 demonstrate a consistency of particle size distribution in the glacial tills, glacial moraine and blown  
299 sand; however, there is greater variability in the particle size distribution of the glaciofluvial and the

300 raised marine deposits. Moraine and blown sand are coarse deposits with no significant silt or clay  
301 components. Raised marine, glaciofluvial and glacial till are mixed fine and coarse deposits with  
302 significant proportions of silt and clay.

303 The soil state descriptions (SSD) of the superficial deposits described at each section are given in  
304 Table 1. They display a high degree of variability both between superficial deposit types and, in many  
305 cases, within a single superficial deposit category. A comparison of SSD indicates: glacial till to be  
306 highly variable but generally denser than other deposits; raised marine and glaciofluvial deposits  
307 have moderate SSD (with greater intra-deposit variability than glaciofluvial deposits). Blown sand  
308 and moraines have the lowest SSD and appear to have less intra deposit variability, although this  
309 could be due to the low sample number.

310 The dynamic cone resistance values are shown in Table 1. There is high variability within each  
311 superficial deposit type, with the exception of blown sand deposits. In general, till deposits have the  
312 highest resistance, followed by glaciofluvial, raised marine, moraine and then finally blown sand  
313 deposits.

314

### 315 **4.3 Multiple Linear Regression**

316 The engineering and hydraulic conductivity data were analysed together using multiple linear  
317 regression (MLR) and Pearson correlation tests. Since particle size and hydraulic conductivity are  
318 both logarithmically distributed, they were log transformed before analysis. There were 27 sites  
319 which had sufficient data to be included in the analysis (Table 1). Table 2 shows the results of the  
320 Pearson correlation tests. All parameters, (except  $d_{60}$ ) were significantly correlated with hydraulic  
321 conductivity. Unsurprisingly there is a high degree of correlation between many of the input  
322 parameters, particularly  $d_{10}$ ,  $d_{15}$  and  $d_{30}$ .

323 The results of stepwise multiple linear regression for hydraulic conductivity, particle size and cone  
 324 resistance (CR) are shown in Table 3. The analysis indicates that, for this dataset, cone resistance  
 325 and  $\log d_{10}$  are the only independent predictors of  $\log K$ . The relationship for the 27 sites is described  
 326 as:

$$327 \log K = 0.97 \log(d_{10}) + (2 - 0.11CR) \quad \text{Equation [1]}$$

328 Where  $D_{10}$  is in mm, CR in MPa and K in m/d. The statistical relationship is strong, with  $R^2 = 0.80$   
 329 when adjusted for the size of the dataset (Figure 11). Independently,  $\log d_{10}$  and CR predict  $\log K$   
 330 with an  $R^2$  of 0.6 and 0.35 respectively. Using soil state description, rather than CR allows a slightly  
 331 larger dataset of 34 for the analysis. A similar relationship is given :

$$332 \log k = 0.79 \log d_{10} + (2.1 - 0.38 SSD) \quad \text{Equation [2]}$$

333 with a similar strength of correlation as for Cone Resistance ( $R^2 = 0.78$ ). Figure 12 illustrates how  
 334 field descriptions of density together with  $D_{10}$  relate to hydraulic conductivity.

335 The proportion of each fraction, (clay, silt, sand, gravel and cobbles) was also calculated for each  
 336 sample, and is reported in Table 1 in the material description. Figure 13 demonstrates an overall  
 337 relationship between the particle size of the largest fraction and hydraulic conductivity, but its  
 338 overall predictive power is weak, as demonstrated by the 4 orders of magnitude between 10<sup>th</sup> and  
 339 90<sup>th</sup> percentile for sand, and the weak correlation ( $R^2 = 0.16$ ).

340

## 341 **5. Discussion**

342 This study of the hydraulic conductivity of heterogeneous superficial deposits, typical of many  
 343 glaciated catchments of NW Europe, has provided useful information on the dominant factors  
 344 controlling permeability across the different deposits, and therefore which properties should be

345 measured to help characterise hydraulic conductivity. In addition, the methodologies developed  
346 within this study have proved an effective way of characterising permeability in a complex  
347 catchment: the integrated geological, hydrogeological and engineering approach; and the field  
348 methods for measuring *in-situ* hydraulic conductivity.

349  
350 The smallest 10% of particle sizes within the deposit and the relative density of the material together  
351 explain much of the variance in hydraulic conductivity for this heterogeneous catchment. Therefore,  
352 modified Hazen formulae, which account for relative density as well as  $d_{10}$ , are likely to be the best  
353 method for estimating permeability in these glaciated environments. This is probably due to the  
354 range of deposits present, and also to the large variability in the relative density of materials formed  
355 within a glaciated environment, where over consolidated glacial tills co-exist next to loose glacial  
356 moraines, or modern alluvium. Additional information on the particle size distribution such as those  
357 found useful by Alyamani and Şen (1993), were found not to help predict hydraulic conductivity.  
358 Our results are consistent with previous studies which highlight the importance of  $d_{10}$  in grain size  
359 analysis to determine hydraulic conductivity (e.g. Hazen, 1892; Vuković and Soro, 1992; Odong,  
360 2007) and the effect of varying degrees of compaction on hydraulic conductivity (e.g. Watabe et al.,  
361 2000; Lu, 2007). These two parameters appear to be the dominant controls on permeability when  
362 considering a wide range of different and heterogeneous superficial deposits. The relationship  
363 remains strong across the range of materials tested and is therefore useful for this heterogeneous  
364 environment. However, for more detailed work in one particular type of material a specific  
365 relationship may give more accurate results (e.g. Vinken and Deitrich 2011).

366  
367 The size of the largest fraction had little predictive power. Therefore, using the bulk descriptors  
368 SAND, SILT, or GRAVEL, to help classify the permeability is of limited use. This was also observed in a  
369 study by Fogg et al. (1998) who found only a weak correlation between these sorts of bulk



370 descriptors and hydraulic conductivity. Particular attention must therefore be given to the presence  
371 of silt or clay, and the degree of consolidation of the material. For this reason, where detailed  
372 information is not available for a catchment, building a conceptual understanding of the superficial  
373 geology, and the palaeo-environment and nature of deposition, can help to generate more  
374 information on the likely presence of fines and the degree of compaction (see Griffiths et al., 2011).  
375 The influence of the finest 10% of the material also has relevance for sampling. Drillers logs, and  
376 samples taken from the drilling and installation of piezometers, often do not record much of the  
377 finest fraction. The fines are held in suspension, or washed away by the drilling process. Therefore  
378 samples are best taken from outcrop, or from cores.

379  
380 The methodology developed to measure hydraulic conductivity of the superficial deposits proved to  
381 be robust and relatively rapid to undertake. Targeting measurements to distinct geological outcrops  
382 identified by a Quaternary geologist ensured that heterogeneity of the catchment could be  
383 confidently reflected in the sampling. Also the repeated Guelph permeameter measurements gave  
384 reassuringly similar results at each outcrop ( $R^2 = 0.9$ ) and could be undertaken rapidly. Therefore,  
385 despite the robust relationship between  $d_{10}$ , relative density and hydraulic conductivity, it may be  
386 more effective to carry out repeated Guelph permeameter measurements at characteristic outcrops  
387 than gathering surrogate information and estimating permeability.

388 The use of soil state descriptors proved reliable, and as significant a predictor when correlated with  
389  $d_{10}$  as cone resistance (Table 2). Therefore, given the difficulties in making *in situ* measurements of  
390 cone resistance, and the wide availability of *soil state* descriptions in borehole and trial pit logs,  
391 observations made in accordance with BS5930:1999 can be used as an adequate substitute for the  
392 measurement of relative density.

393 The wide range and heterogeneous nature of the deposits tested suggests that our findings may be  
394 fairly widely applicable in superficial deposits. However it would be useful to obtain more data in

395 blown sand and glacial moraine deposits and other deposit types that were not tested (e.g. fluvial  
396 deposits).

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## 398 6. Conclusions

399 This study has investigated the hydraulic conductivity of superficial deposits in a heterogeneous  
400 catchment in northern Scotland, typical of many catchments subjected to past glaciations in North  
401 West Europe. In total, 38 different deposits were sampled at 25 sections. The deposits comprised:  
402 glacial tills and moraines; glaciofluvial and glaciolacustrine deposits; raised marine deposits; and  
403 blown sand. Hydraulic conductivity measurements were made using repeated Guelph Permeameter  
404 measurements, cone resistance was measured *in situ* with a Panda dynamic cone penetrometer (to  
405 give an indication of relative density); material descriptions were made in accordance with  
406 BS5930:1999; and disturbed samples were taken for particle size analysis. The following conclusions  
407 can be drawn:

- 408 1. *In situ* measurements of hydraulic conductivity made with a Guelph permeameter at deposit  
409 outcrops proved highly repeatable ( $R^2 = 0.9$ ).
- 410 2. Hydraulic conductivity (K) ranged from 0.001 m/d to > 40 m/d; glacial till had the lowest K  
411 (median 0.027 m/d) and glacial moraine the highest K (median 30 m/d).
- 412 3. The results of stepwise multiple linear regression for hydraulic conductivity, particle size and  
413 cone resistance indicate that, for this dataset, cone resistance and  $\log d_{10}$  are the only  
414 independent predictors of  $\log K$  [ $\log K = 0.97 \log(d_{10}) + (2 - 0.11CR)$ ], where  $d_{10}$  is in mm, CR in  
415 MPa and K in m/d. The statistical relationship is strong, with  $R^2 = 0.80$  when adjusted for the size  
416 of the dataset.
- 417 4. Using soil state material descriptions made in accordance with BS5930:1999 instead of the cone  
418 resistance to give an indication of relative density gave a similar relationship and strength of  
419 correlation ( $R^2 = 0.78$ ). Therefore high quality soil state descriptions are a good surrogate for  
420 cone resistance measurements.

421 5. The size of the largest fraction had little predictive power. Therefore, using the bulk descriptors  
422 SAND, SILT, or GRAVEL, to help classify the permeability of unconsolidated heterogeneous  
423 sediments is of only limited use.

424 6. *In situ* Guelph permeameter measurements at outcrops with careful geological characterisation  
425 provide a good method of determining the permeability characteristics of superficial deposits  
426 where large-scale permeability testing is not feasible.

427 With the growing recognition of the importance of the hydraulic conductivity of superficial deposits  
428 to many aspects of catchment hydrology and hydrogeology, robust methods of characterising  
429 hydraulic conductivity will become increasingly important. The methodologies and relationships  
430 developed within this paper should help to inform future studies of catchment permeability.

431

432

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437

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593 **Figure Captions**

594

595 Figure 1: Simplified superficial geological map of the study area.

596 Figure 2: Schematic cross section across the area illustrating the general succession of deposits.

597 Figure 3: Guelph Permeameter measuring hydraulic conductivity of the grey coloured Ardersier Silts  
598 at Cloddymoss (locality 20, Figure 1) with ledges below excavated into the underlying orange  
599 coloured till.

600 Figure 4: Ledge and hole excavated into raised marine sands.

601 Figure 5: Panda Penetrometer test undertaken in till

602 Figure 6: Results of cone resistance tests using the Panda2 instrument at the Grangehall Ditch  
603 glaciofluvial site (site 11 on Figure 1) and the Ardersier Silt Race Track site (Site 15 on Figure 1).

604 Figure 7: Example plots of water depth in the Guelph Permeameter reservoir with time used to  
605 determine the steady intake rate of water, with the resulting hydraulic conductivity values (K).

606 Repeated measurements (A and B) within the same deposit at the same site show largely consistent  
607 results.

608 Figure 8: Comparison of duplicate hydraulic conductivity measurements (A and B) taken in the same  
609 material at the same section, generally sampled within 5 m of each other.

610 Figure 9: Box plot of hydraulic conductivity (one value per site) for superficial deposits in Morayshire.  
611 The number of sites where hydraulic conductivity was measured is shown in brackets. (Glaciofluvial  
612 material includes both fluvial and lacustrine deposits).

613 Figure 10: Particle Size Distribution envelopes for each superficial deposit type.

614 Figure 11: Relationship between *predicted* hydraulic conductivity (using  $d_{10}$  and Cone Resistance  
615 (CR)) and *measured* hydraulic conductivity (K) for 27 sites in heterogeneous superficial deposits in  
616 Morayshire.

617 Figure 12: Relationship between hydraulic conductivity,  $d_{10}$  and soil state descriptor as observed in  
618 the field.

619 Figure 13: Box plots of hydraulic conductivity plotted for particle size of the largest fraction in each  
620 sample. Note that this has much less predictive power ( $R^2 = 0.16$ ) than using  $d_{10}$  and CR ( $R^2 = 0.8$ ).

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Table 1: Results

Locality (and site number on Fig. 1)	Lithology	Strength description	<i>In situ</i> k (m/day)	<i>In situ</i> Cone Resistance (Mpa)	d <sub>10</sub>	d <sub>60</sub>	Material Description
Rivermeads (1)	Glacial Till	Dense	0.102	6.2	0.0060	0.5894	Gravelly (f-c) very silty SAND (f-m) with some COBBLES
Rivermeads (1)	Glaciofluvial	Loose	1.04	2.32	0.0019	0.1700	Gravelly (f-m) very silty SAND (f-m)
Highland Boath (2)	Glacial Moraine	Very Loose	26.8		0.4104	16.8732	SAND (f-c) and GRAVEL (m-c) with some cobbles
Riereach Burn Site 1 (3)	Glacial Till	Very Dense	0.01	10.555	0.0011	0.7693	Very clayey very gravelly (f-c) SAND (f-c)
Riereach Burn Site 1 (3)	Glacial Till	Very Dense	0.051	9.52	0.0096	1.3623	Silty very gravelly (f-c) SAND (f-c)
Riereach Burn Sand Pit (4)	Glaciofluvial	Loose	31.1	3.61	0.1863	0.5880	N/A
Drynachan (5)	Glacial Till	Dense	1.3	6.21	0.0186	0.3025	Gravelly (f-m) very silty SAND (f-m)
Drynachan (5)	Glacial Till	Dense	0.054	7.52			Gravelly (f-m) very silty SAND (f-m)
Drynachan (5)	Glacial Till	Very Dense	0.015	12.63	0.0106	0.3534	Gravelly (f-m) very silty SAND (f-c)
Riereach Burn Site 2 (6)	Glacial Till	Dense - Very Dense	0.12	9.99	0.0024	0.7711	Very silty very gravelly (f-c) SAND (f-c)
Dunearn (7)	Glaciolacustrine	Firm	0.042	9.08	0.0010	0.0083	Slightly clayey SILT
Dunearn (7)	Glaciolacustrine	Loose	2.51		0.0232	0.1383	Silty SAND (f)
Dunearn (7)	Glaciolacustrine	Loose	30.2		0.2581	0.5153	SAND (m-c)
Easterton (8)	Glacial Till	Loose - Med. Dense	0.151	2.84	0.0038	0.2498	Gravelly (f-c) very silty SAND (f-m) with some cobbles
Findhorn Raised Marine (9)	Raised Marine	Medium Dense	3.2	12.545	0.1759	16.6746	SAND (f-m) and GRAVEL (m-c)
Findhorn Raised Marine (9)	Raised Marine	Very Loose	4.97	1.11	0.1355	0.2045	SAND (f-m)
Chapleton Mountain Bike (10)	Glaciofluvial	Medium Dense	1.77	7.575	0.2653	11.3743	Very sandy (f-c) GRAVEL (f-c) with a little cobbles
Grange Hall Ditch (11)	Glaciofluvial	Loose	0.432	3.22			Gravelly SAND (not fully recorded)
Grange Hall Ditch (11)	Glaciofluvial	Loose	0.048	1.595	0.0025	0.3045	Silty gravelly (f-c) SAND (f-m)
Findhorn Blown Sand (12)	Blown Sand	Very Loose	8.55	0.75	0.1339	0.2043	SAND (f-m)
Findhorn Blown Sand 2 (13)	Blown Sand	Very Loose	9.46	0.65			SAND (f-m)
Ardersier Silt (14)	Raised Marine	Soft - Firm	0.575	2.98	0.0015	0.0279	Slightly sandy slightly clayey SILT
Ardersier Silt Race Track (15)	Raised Marine	Very Loose	2.33	4.98	0.0388	0.1780	Silty SAND (f-m)
Dunearn Pit (16)	Glaciofluvial	Loose	8.06	1.48	0.1113	0.2039	SAND (f-m)
Dunearn Pit (16)	Glaciofluvial	Dense	5.53		0.7146	33.7607	Very sandy (m-c) GRAVEL (f-c) with some cobbles
Riereach Road Moraine (17)	Glacial Moraine	Very Loose	>40	2.6	0.6856	6.0503	Very sandy (m-c) GRAVEL (f-c)
Riereach Road Moraine (17)	Glacial Moraine	Loose - Med. Dense	0.147	13.68	0.1175	12.1595	Silty very gravelly (c) SAND (f-c)
Culbin Forest (18)	Blown Sand	Very Loose	4.41	0.99	0.1491	0.2207	SAND (f-m)
Grange Hill (19)	Glacial Till	Dense - Very Dense	0.027	3.33	0.0010	0.2077	Gravelly (f-m) very silty SAND (f-m)
Cloddymoss (20)	Glacial Till	Dense	0.0012	9.8	0.0019	0.2935	Gravelly (f-c) very silty SAND (f-c)
Cloddymoss (20)	Raised Marine	Stiff	0.013	2.695	0.0010	0.0176	Slightly sandy (f) slightly clayey SILT
Cothall (21)	Glaciofluvial	Loose	4.93		0.1727	0.4087	Slightly gravelly (f) slightly silty SAND (m)
Cothall (21)	Glacial Till	Firm - Stiff	0.006	11.87	0.0010	0.2175	Slightly gravelly (f-m) slightly clayey sandy (f-c) SILT
Croft Road Wood (22)	Raised Marine	Loose	1.1	3.74	0.0289	0.1619	Slightly clayey silty SAND (f-m)
Altyre Estate Site No. 3 (23)	Glacial Till	Very Dense	0.004				Slightly silty gravelly (f-c) SAND (f-c)
Altyre Estate Site No. 1 (24)	Glacial Till	Dense	0.004		0.0051	0.5129	Very silty very gravelly (f-c) SAND (f-m)
Wind Farm (25)	Raised Marine	Loose	2.94	1.46	0.1365	0.2106	SAND (f-m)
Wind Farm (25)	Raised Marine	Loose	1.04		0.2457	22.2066	Very sandy (m) GRAVEL (m-c)

Table 2: Pearson correlation matrix for *in situ* hydraulic conductivity and engineering parameters for 27 samples in Morayshire

	Cone Resistance	Soil State Description	Log d <sub>10</sub>	Log d <sub>15</sub>	Log d <sub>30</sub>	Log d <sub>60</sub>	Log K
Cone Resistance	1.00	0.64	-0.21	-0.23	-0.05	0.42	-0.53
Soil State Description	0.64	1.00	-0.60	-0.59	-0.34	0.04	-0.74
Log d <sub>10</sub>	-0.21	-0.60	1.00	0.94	0.78	0.56	0.83
Log d <sub>15</sub>	-0.23	-0.59	0.94	1.00	0.87	0.62	0.78
Log d <sub>30</sub>	-0.05	-0.34	0.78	0.87	1.00	0.82	0.61
Log d <sub>60</sub>	0.42	0.04	0.56	0.62	0.82	1.00	0.25
Log K	-0.53	-0.74	0.83	0.78	0.61	0.25	1.00

**Significance level**

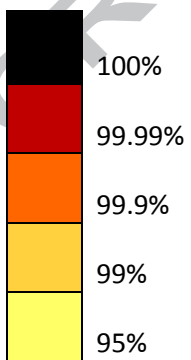
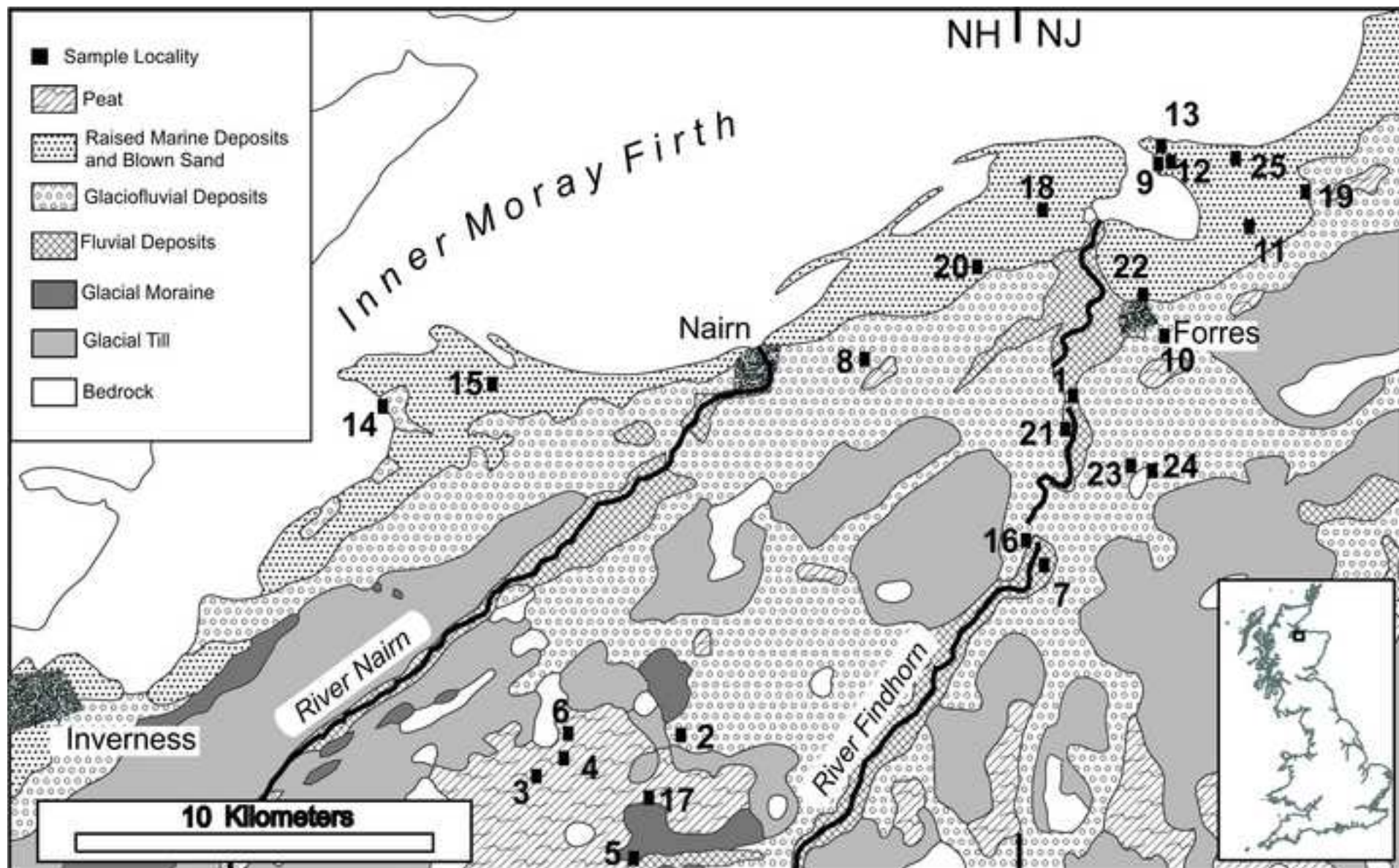


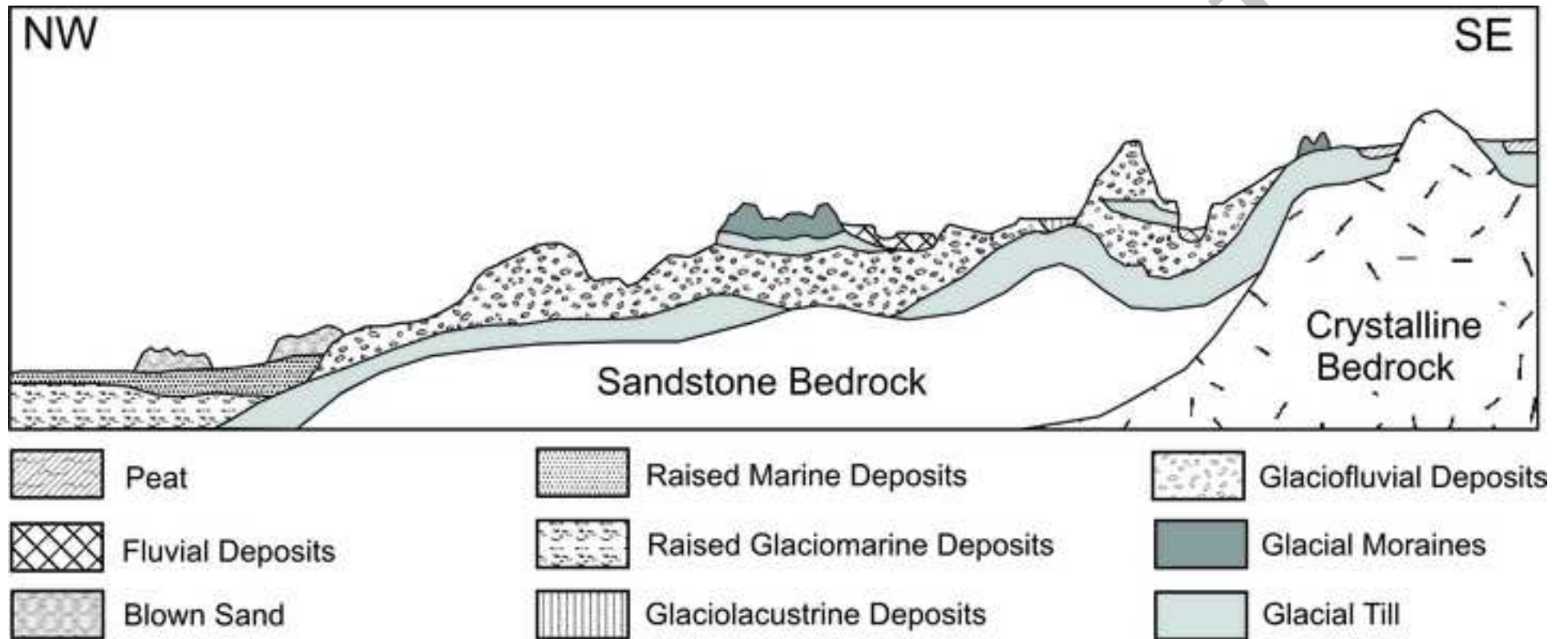
Table 3: P values for multiple linear regression analysis of the Morayshire dataset for log K and various material properties. The sign indicates whether the predictor is directly (+) or inversely (-) related.

Source	Value	Standard error	t	Pr >  t
logd10	1.123	0.349	3.216	<b>0.004</b>
Cone Res (MPa)	-0.096	0.046	-2.091	<b>0.049</b>
logd15	-0.313	0.519	-0.602	0.553
logd30	0.456	0.630	0.723	0.478
logd60	-0.235	0.430	-0.547	0.590

**Bold** are those significant at the 95% level



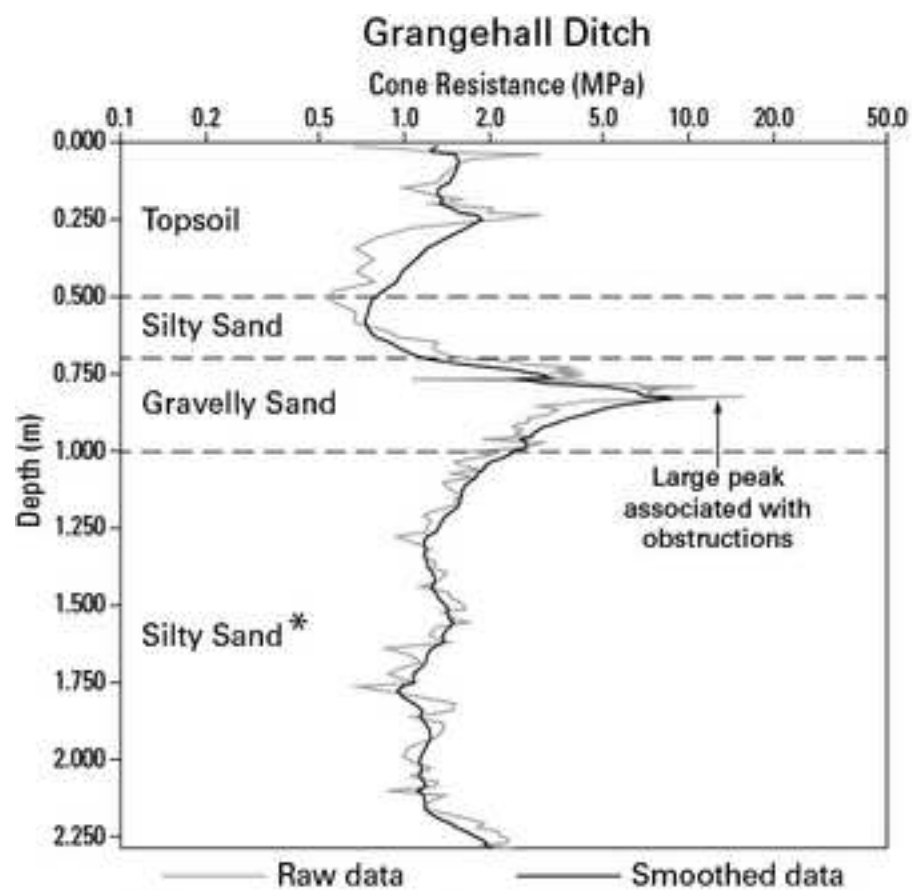




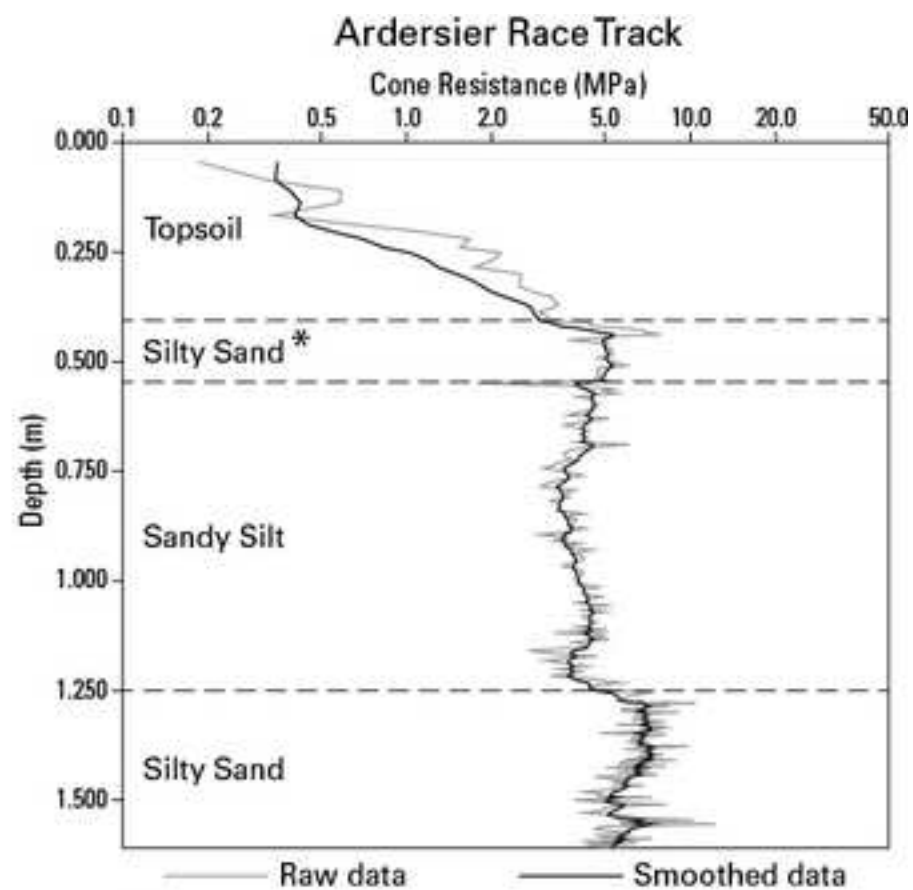






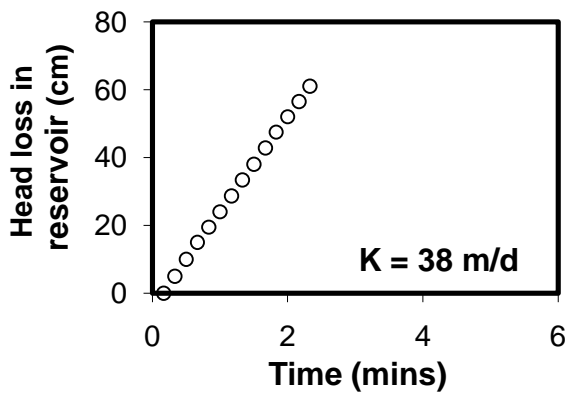


\* Target layer for Guelph permeameter and geotechnical testing

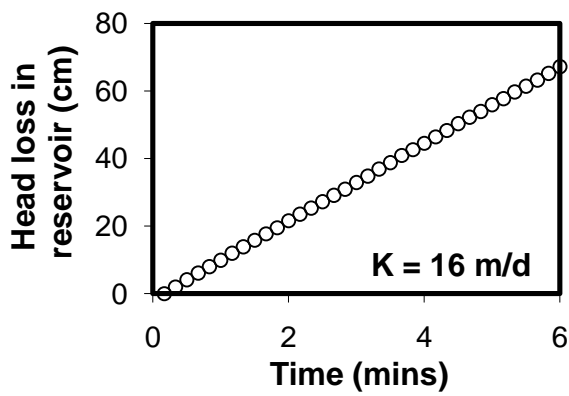


\* Target layer for Guelph permeameter and geotechnical testing

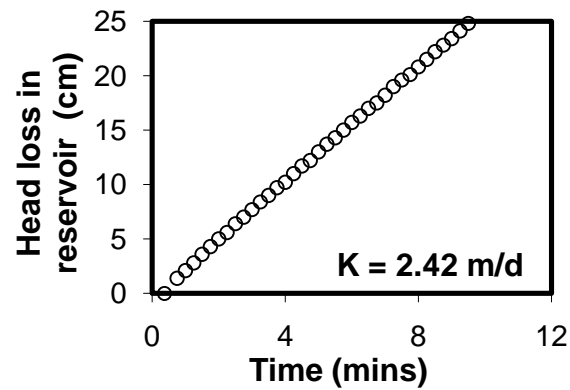
Highland Boath Moraine 1



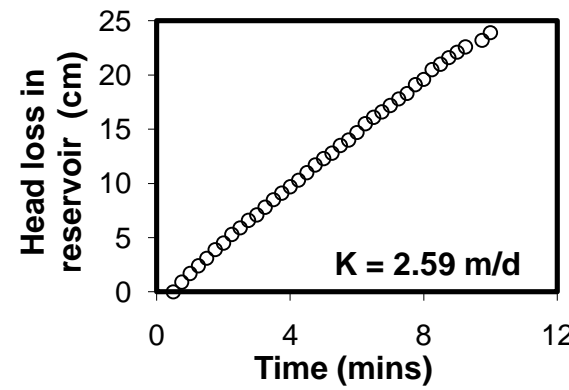
Highland Boath Moraine 2



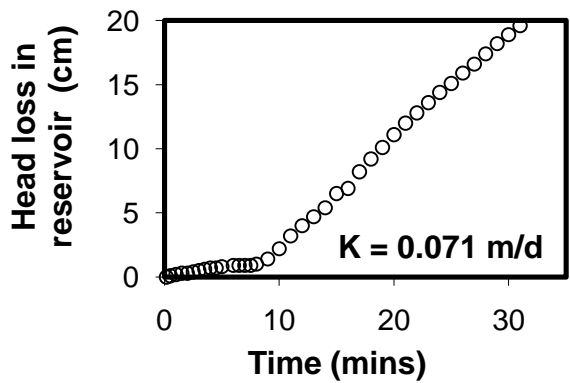
Dunearn Fine-Medium Sand 1



Dunearn Fine-Medium Sand 2



Grange Hill Red Till 1



Grange Hill Red Till 2

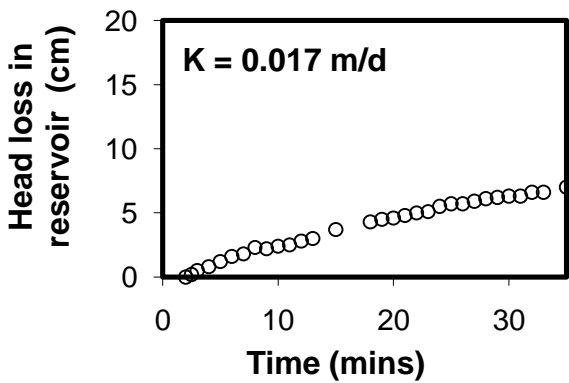
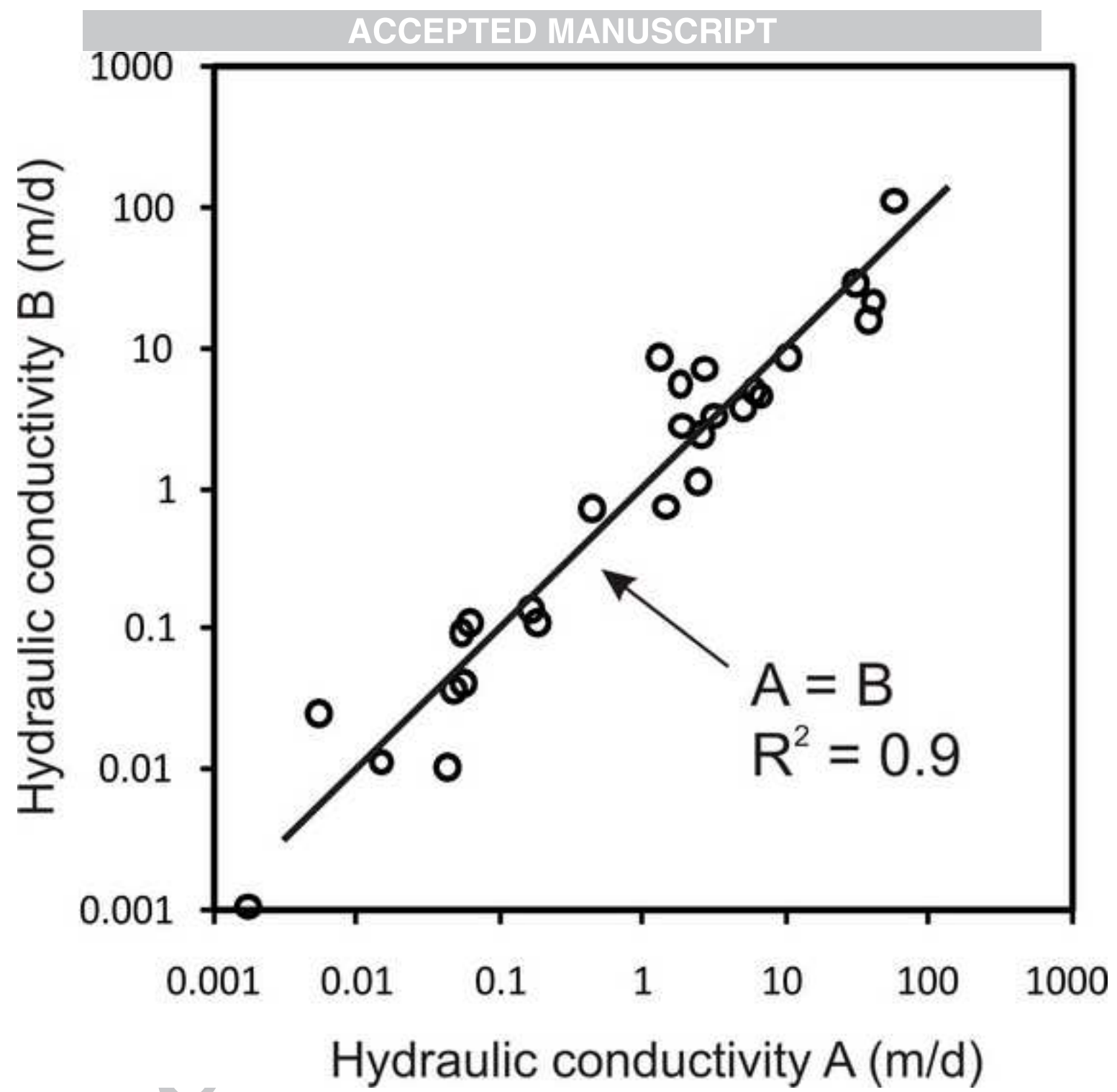
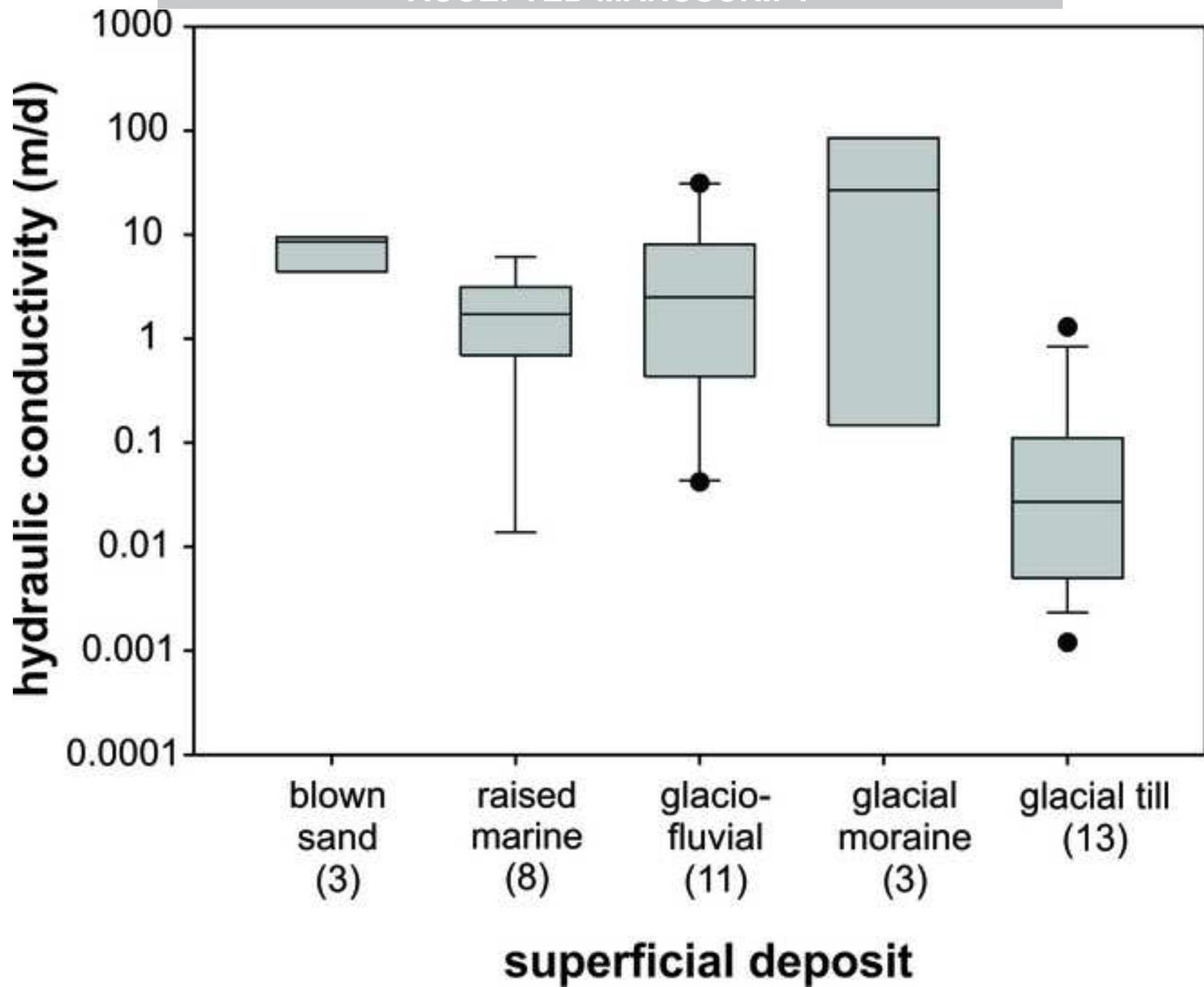


Figure8







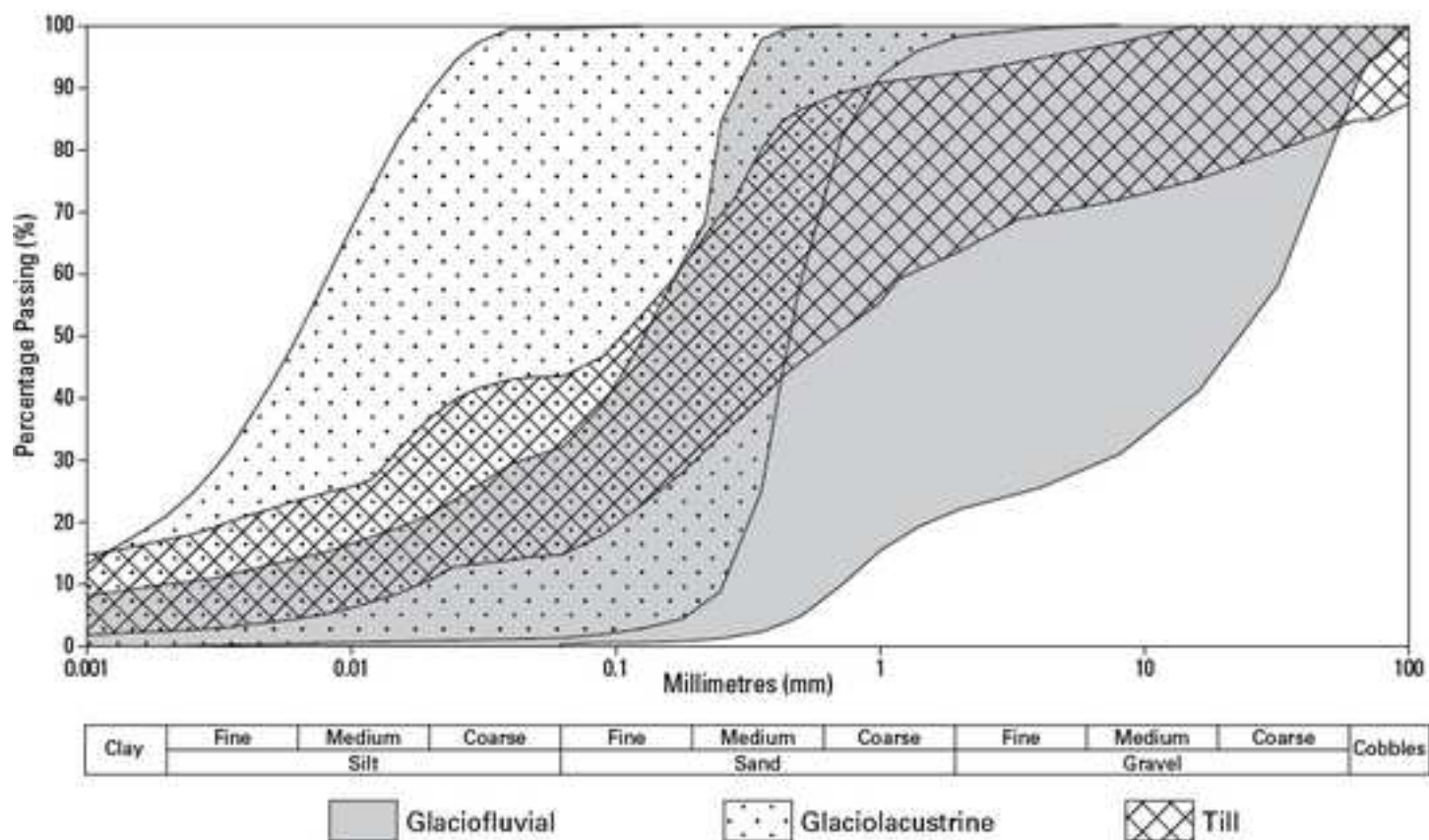
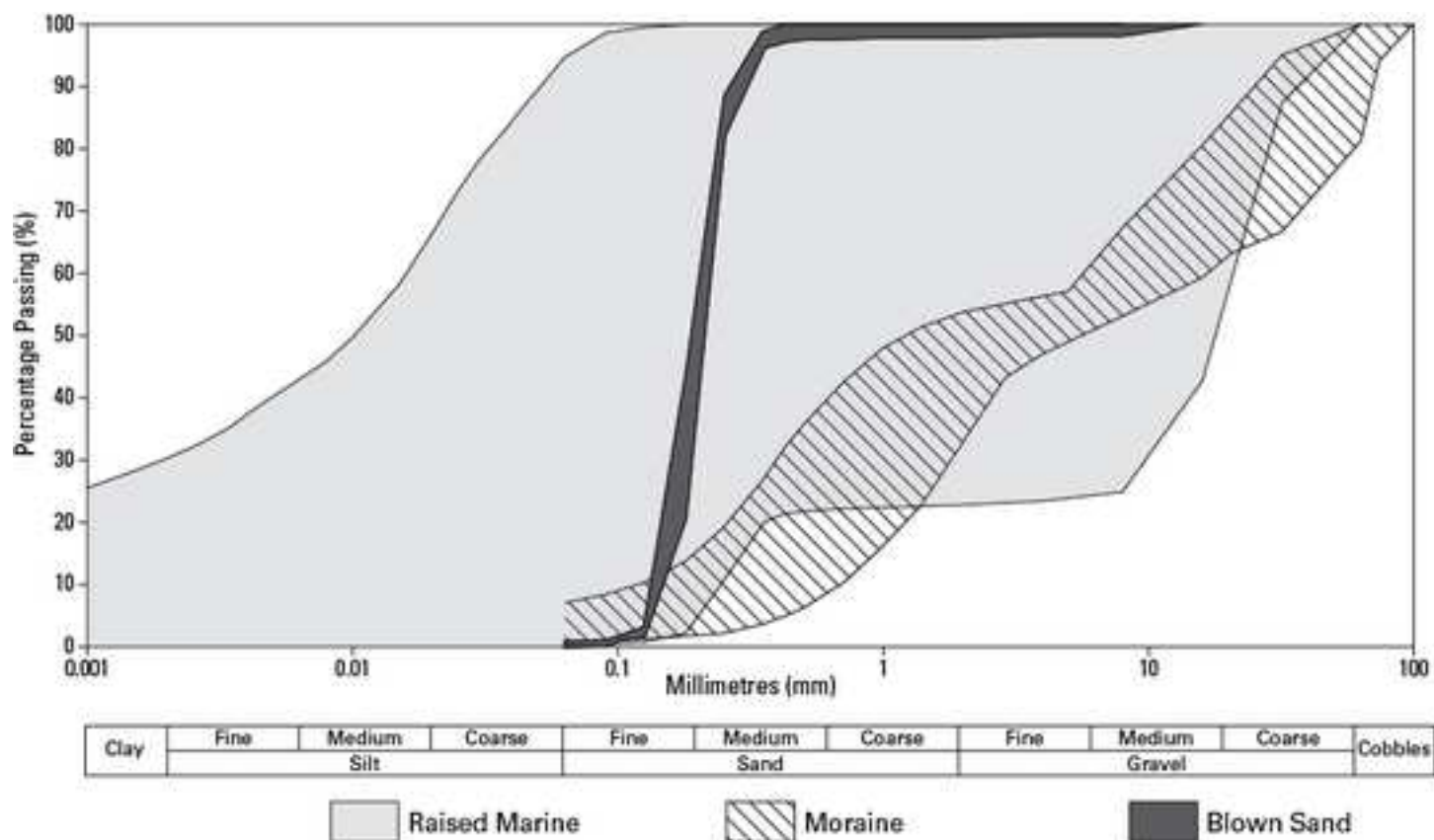
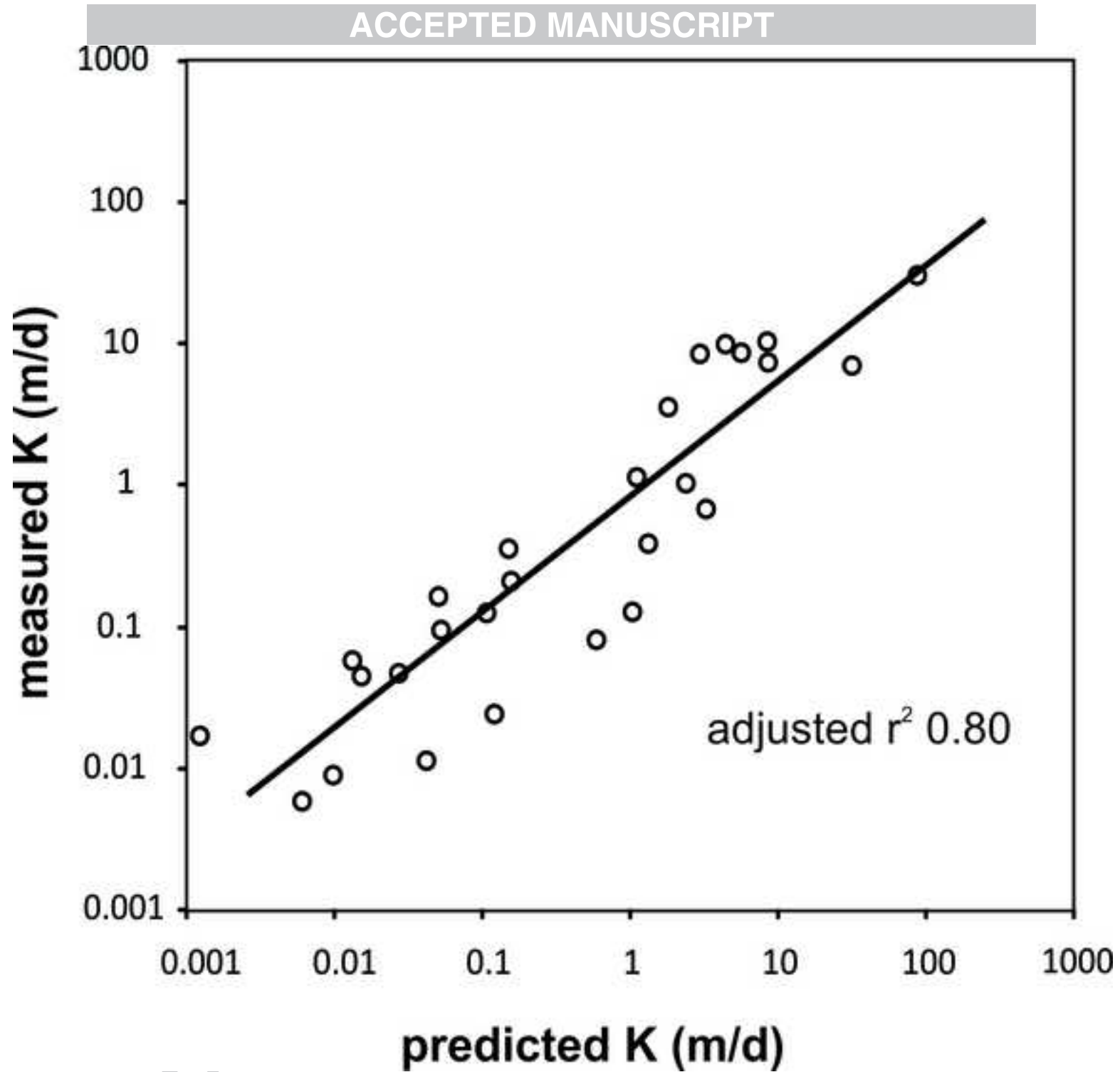
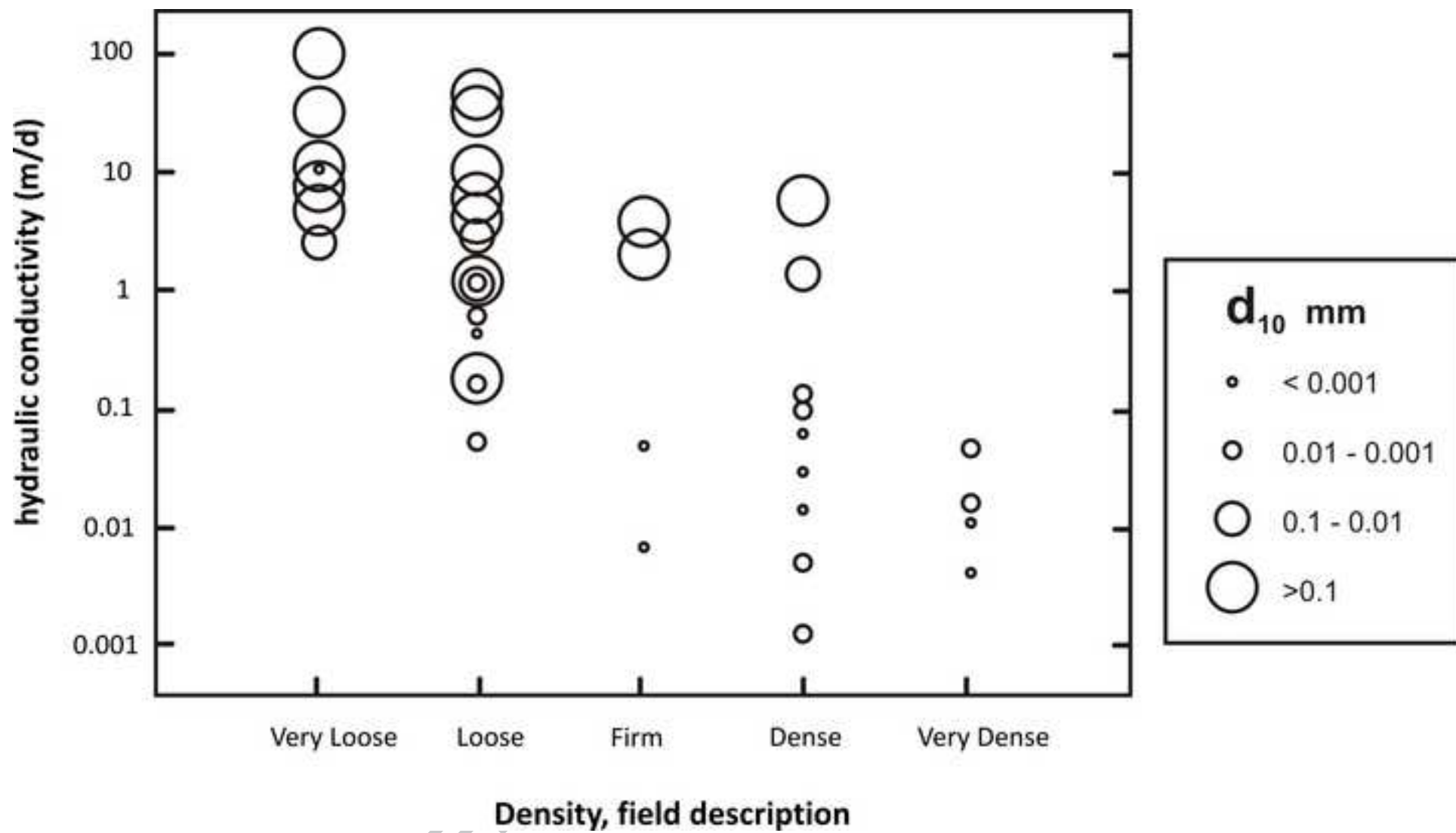
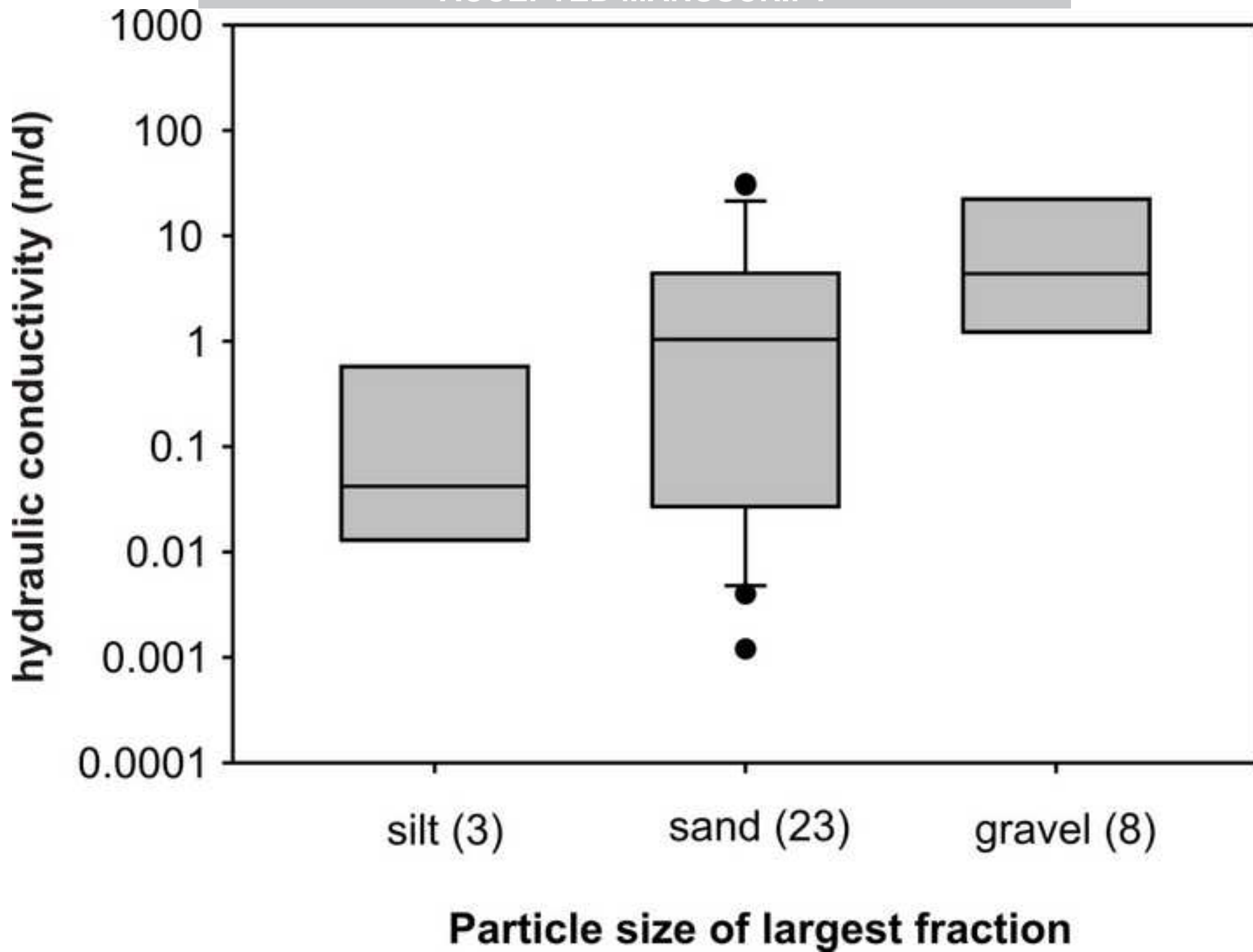


Figure11







**Highlights**

We examine the permeability of superficial deposits in a heterogeneous catchment

K ranges from 0.001 to > 40 m/d, highest in glacial moraine, lowest in till

MLR showed that K was related to  $\log d_{10}$  and relative density with  $r^2$  of 0.80

Material description of largest fraction had little predictive power of K

ACCEPTED MANUSCRIPT