

1 **Water level monitoring pressure transducers – a need for industry-wide standards**

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4 **ABSTRACT**

5 There are currently no industry-wide standards for the calibration and specification of water  
6 level monitoring pressure transducers. Consequently, specifications from different  
7 manufacturers are currently not directly comparable and different branded sensors may not  
8 perform similarly under the same environmental conditions. This has been highlighted by the  
9 varied performance of fourteen leading brands of pressure transducers under test conditions.  
10 In laboratory tests transducers generally met product accuracy specifications, although  
11 temperature compensation was substandard in five absolute sensors. In a 99-day field test,  
12 accuracy was typically within around  $\pm 10$  mm for lower range pressure sensors, which  
13 exceeded some product specifications. Furthermore, there was evidence for linear and curved  
14 forms of instrument drift. As a result of the diverse performance of the transducers, it is  
15 recommended that an industry-wide standard for calibration and specification is introduced.  
16 This would eliminate any uncertainty surrounding the current procedures and lead to more  
17 informed procurement by the user who would have a greater understanding of comparative  
18 instrument performance. Any new standard should also address sensor drift which is  
19 currently rarely cited in product specifications.

20 **INTRODUCTION**

21 Pressure transducers are widely used in hydrogeological and hydrological sciences for  
22 monitoring water levels. The technology converts an applied fluid pressure, generally across  
23 a sensor diaphragm, to an electrical signal and then to an actual pressure. This assumes a

24 water density, which is generally estimated from the measured water temperature and an in-  
25 built compensation algorithm. The effects of water salinity can also be addressed, but it is  
26 normally assumed to be constant during continuous measurements.

27 Submersible pressure transducers are mainly either absolute (non-vented) or gauged (vented)  
28 (Figure 1). An absolute device records the combined atmospheric pressure and pressure  
29 exerted by the overlying water column and the data have to be corrected using a separate  
30 record of atmospheric pressure – usually data collected from a nearby barometric pressure  
31 transducer. Gauged transducers are vented to the surface to eliminate the effects of  
32 atmospheric pressure across the sensor diaphragm and record just the pressure exerted by the  
33 overlying water column.

34 Monitoring water levels with pressure transducers has been applied to: national groundwater  
35 resource management (Kim et al. 1995), aquifer testing (Robbins et al. 2008), groundwater-  
36 surface water interaction studies (Hunt et al. 2006; Allen et al. 2010), investigating  
37 groundwater recharge (Crosbie et al. 2005), deriving surface water ratings curves (Guan et al.  
38 2010) and estimating lake storage (Hood et al. 2006) amongst many others. Additionally,  
39 many transducers also measure water temperature which can be a useful natural tracer  
40 (Becker et al. 2004; Constantz 2008).

41 The diverse application of pressure transducers reflects the range of user needs. Water level  
42 measurement accuracy could be required to range from several centimetres in national  
43 groundwater resource management to a centimetre or possibly less for a detailed small-scale  
44 study. The higher degrees of accuracy should be achievable according to various transducer  
45 product specifications. However, field experience indicates specifications are rarely  
46 attainable in the field due to issues with transducer accuracy, precision, temperature  
47 compensation and drift.

48 There are currently no agreed industry-wide standards relating to the specification and  
49 calibration of water level monitoring pressure transducers. Product calibration and  
50 specification are undertaken by the individual manufacturer according to production costs  
51 and customer feedback. Consequently specifications from different manufacturers are  
52 currently not directly comparable and different branded sensors may not perform similarly  
53 under the same environmental conditions; although it is realised that product design and  
54 internal algorithms would also have an influence. This paper highlights uncertainties between  
55 sensors by testing a range under laboratory and field conditions and advocates a need for  
56 internationally agreed calibration and specification standards.

## 57 TEST METHODOLOGY

58 Fourteen different leading brand models of submersible pressure transducers were tested. Six  
59 were vented and the remainder were absolute (Table 1). Generally, sensors were low pressure  
60 range models (less than 15 m H<sub>2</sub>O), although one was 30 m H<sub>2</sub>O range and one was 100 m  
61 H<sub>2</sub>O range. Five different barometric transducer units were also tested. Where possible, two  
62 of each submersible sensor was tested to ensure repeatability.

63 An experimental test bed was established in the laboratory to examine the responses of the  
64 sensors to changes in pressure and temperature in a controlled environment. It comprised a  
65 sealed Perspex tube, 2 m in length, partially filled with water (Figure 2). The tube was of  
66 sufficient length to allow all sensors to be tested simultaneously. Moreover, barometric units  
67 could be fixed within the tube where air temperature variations were subdued by the water  
68 column.

69 The test bed was located in a temperature controlled laboratory in order to minimise the  
70 external influence of atmospheric temperature on the water column, which could otherwise  
71 result in small head changes. Provisional testing showed that daily water column temperature

72 variations were under 1°C in this laboratory. Prior to any testing, the column was filled at  
 73 least one week in advance to allow the water temperature to equilibrate. A mercury  
 74 thermometer was also placed in the tube to manually monitor water temperature.

75 Table 1 - Transducers tested

Transducer	No. tested	Type	Range (m H <sub>2</sub> O)
A	2	Vented	3.5
B	2	Vented	3.5
C	2	Vented	3
D	2	Vented	2
E	2	Vented	11
F	2	Vented	3
G	1	Absolute	10
H	2	Absolute	14
I	1	Absolute	30
J	2	Absolute	5
K	2	Absolute	100
L	2	Absolute	10
M	2	Absolute	10
N	2	Absolute	5
O	1	Absolute/Barometric	4
P	1	Barometric	10
Q	1	Barometric	1.5
R	1	Barometric	1.5
S	1	Barometric	1.5

76 A peristaltic pump was installed to allow water to be introduced and removed from the  
 77 column at a controlled rate. The end of the pump intake tube was positioned above the  
 78 transducers to minimise disturbance during abstraction. An Advent 5 m Class I measuring  
 79 tape was fixed to the tube to reference any changes in water level. These tapes are calibrated  
 80 to  $\pm 0.22$  mm over the first metre and  $\pm 0.25$  mm over the second metre.

81 Transducer accuracies were evaluated by lowering the water level by a sequence of set steps  
 82 (10, 20, 50, 200, 1000 mm) and comparing against measured level changes. Each step change  
 83 was held for a total of 90 minutes, including 30 minutes for sensors to equilibrate. All  
 84 instruments were set to log at 30 second intervals. Step changes recorded by each sensor were  
 85 calculated as the average of 120 pressure readings following the equilibration period. The

86 total error associated with two manual readings of the Class I measuring tape at the beginning  
87 and end of each step change was assumed to be 1 mm.

88 Precision was assessed by maintaining a fixed head over a 12.5 hour period and examining  
89 the recorded level variation or 'noise'. Sensors were set to log at 30 second intervals.  
90 Precision was calculated as three standard deviations of 1440 pressure readings, following a  
91 30 minute equilibration period. Water temperature changes over the testing period were also  
92 noted. Barometric transducer data were verified before the absolute sensors were  
93 compensated.

94 The accuracy of temperature compensation for pressure readings was tested by filling the  
95 column with chilled water and allowing it to warm towards ambient room temperature. This  
96 resulted in a water temperature change of between 6 and 7 °C. The increase in temperature  
97 altered the fluid density and consequently the height of water in the column. Nevertheless, the  
98 pressure readings should have remained the same if internal temperature correction  
99 algorithms are accurate. Therefore, any instrument recorded pressure variation should be very  
100 similar to variations recorded during the precision experiment.

101 Sensors were set to log at 30 second intervals over a period of 12.25 hours. The variation in  
102 level was assessed as three standard deviations of 1440 pressure readings, following a 15  
103 minute equilibration period. This was compared with the precision tests to assess  
104 significance.

105 The field test was carried out in a borehole open to the confined Cretaceous Upper Greensand  
106 aquifer. The shallow water table and known daily fluctuations in the order of tens of  
107 centimetres were considered ideal for testing purposes.

108 All instruments were simultaneously installed in the secure borehole to similar depths.  
109 Barometric pressure transducers were deployed in a nearby building for security purposes,  
110 but at the same elevation as the borehole cap. These sensors were initially in a temperature  
111 controlled room, but were later exposed to the ambient air temperature within the same  
112 building. The submersible pressure transducers were left undisturbed in the borehole for 99  
113 days. The borehole annulus was regularly dipped to the nearest millimetre using the same  
114 Solinst® dip tape to the same reference point. The dip tape was subsequently validated  
115 against a Class I measuring tape.

116 All sensors were set to log at a 15 minute interval and pressure readings were referenced to  
117 the depth to water using a dip measurement approximately 40 hours after all sensors had been  
118 installed. The instrument error throughout the test was calculated as the difference between  
119 the dip measurement and the reading of the transducer. The pressure transducer accuracy was  
120 subsequently calculated as two standard deviations of the instrument error (80 data points).  
121 This is less stringent than the laboratory accuracy testing due to the greater experimental  
122 error, which was considered to be up to 5 mm (human error), but generally less than 3 mm.

## 123 RESULTS & DISCUSSION

124 The results of the laboratory testing are summarised in Table 2. All accuracy and precision  
125 data are presented as the mean of two repeat tests. Only errors in accuracy testing of 2 mm or  
126 greater are reported, as the experimental error was considered to be 1 mm. Significance in the  
127 temperature compensation trial refers to whether the variation in level exceeded the precision  
128 results by over 2 mm.

129 All but two of the sensors (Transducer A and one of Transducer L) achieved their product  
130 accuracy specification. No errors could be detected in two of the vented and one of the  
131 absolute sensors. Precision results were varied and ranged from 0.4 to 74.2 mm, although the

132 lower pressure range sensors ranged between  $\pm 0.4$  and  $\pm 7.3$  mm. Excluding two of the  
133 models, precision was consistently under  $\pm 1.5$  mm for the lower pressure range transducers.

134 Precision appeared to be influenced by the pressure range of the sensor, while vented  
135 transducers generally performed better than unvented transducers. The results of the  
136 temperature compensation testing were significant for five of the absolute sensors. Figure 3  
137 illustrates a pressure transducer with poor temperature compensation: during reasonably  
138 stable temperatures pressure readings are also stable but when water temperatures vary,  
139 pressure readings vary significantly and actually exceeded the product accuracy specification.

140 The results of the field testing are summarised in Table 3. The field accuracy results are  
141 inferior to the laboratory accuracy results and some sensors do not meet the accuracy  
142 specifications of the manufacturer. Nevertheless, field accuracy is still around  $\pm 10$  mm or  
143 less, with the exception of the higher range pressure transducers. The most accurate sensors  
144 were Transducers F and H.

145 Sensor accuracy deteriorated over time in many units, i.e. sensors drifted (Figure 4). This is  
146 something many pressure transducer manufacturers do not cite in product specifications.  
147 Consequently, an attempt has been made to characterise drift over the experimental  
148 timeframe (Table 3). This was undertaken by calculating the median of the final five  
149 instrument errors at the end of the test. It was noted to vary between negligible and 27 mm,  
150 although the higher range sensors drifted by up to 181 mm. The rate of drift also varied  
151 between units, with some appearing to show linear or some curved forms (Figure 4).

152 It is noted that the estimated drift will inherently also take sensor accuracy into account.  
153 Moreover, drift may differ significantly between locations as a result of the geochemical and  
154 hydrogeological setting. In the test locality, iron biofilms and calcite scaling could have

155 caused an issue with some sensors. Movement of the hanging cables can also not be ruled out  
156 completely, although there are no apparent sudden increases in instrument error.

157 Over the first 24 hours of the field test the five barometric transducers ranged by an average  
158 of 43 mm H<sub>2</sub>O, or 21 mm H<sub>2</sub>O when not including Transducer Q. This represents a  
159 significant difference in pressure. Moreover, the difference between transducers varied over  
160 time, and reached as much as 67.4 mm (Figure 5).



161 Table 2 Summary of laboratory test results

Transducer	Accuracy in water level change (mm)					Precision (mm)	Temperature compensation		
	10	20	50	200	1000		Temperature Change (°C)	Variation in level (mm)	Significant?
A	-	-	-	-	7	± 0.7	7.3	± 0.3	N
	-	-	-	-	6	± 0.7	6.7	± 2.6	
B	-	-	-	-	-	± 0.5	7.3	± 1.8	N
	-	-	-	-	-	± 0.6	7.1	± 1.4	
C	-	-	-	-	-	± 0.6*	7.0	± 0.5	N
	-	-	-	-	-	± 0.4	6.7	± 0.5	
D	-	-	-	-	3	± 1.5	n/a	± 1.3	N
	-	-	-	-	2	± 1.5	n/a	± 0.7	
G <sup>+</sup>	-	-	-	-	-	± 3.6	6.1	± 6.4	Y
H	-	-	-	-	2	± 1.2	6.9	± 1.3	N
	-	-	-	-	-	± 1.2	6.7	± 1.8	
I	2	2	-	8	7	± 15.8	6.3	± 44.8	Y
J	-	-	-	-	5	± 6.4	6.1	± 11.3	Y
	-	-	-	-	5	± 7.3	7.3	± 10.4	Y
K	7	6	10	31	20	± 37.6	6.5	± 136.7	Y
	12	1	5	21	25	± 39.0	6.5	± 97.6	Y
L	2	-	8	20	7	± 74.2	6.7	± 90.8	Y <sup>#</sup>
	-	-	-	-	3	± 7.6	6.5	± 7.1	N
M	-	-	-	-	2	± 6.1	6.6	± 5.9	N
	-	-	-	-	3	± 6.4	6.1	± 5.9	N
N	-	-	-	-	3	± 0.8	5.9	± 5.1	Y
	-	-	-	-	-	± 0.7	5.7	± 7.1	Y
O <sup>+</sup>	-	-	-	-	-	± 4.5	2.6	± 5.8	N

162 Notes: dash denotes a mean error of less than 2 mm; <sup>+</sup> data compensated with barometric Transducer P; \* results of only one precision experiment; <sup>#</sup> classed as technically  
 163 significant for the individual sensor but not for the model as a whole, as particular sensor appears to be malfunctioning; Transducers E and F not tested.

164 Table 3 Results of field testing on pressure transducers

Transducer	Field accuracy (mm)	Estimated drift (mm)
A	± 9	12
	± 10	14
B	± 22 <sup>+</sup>	15
	± 12	19
C	± 8 <sup>#</sup>	13 <sup>#</sup>
	± 9 <sup>#</sup>	13 <sup>#</sup>
D	± 9	10
E	± 27	27
	± 28 <sup>s</sup>	27 <sup>s</sup>
F	± 4	6*
	± 4	5*
G	± 7	-5
H	± 5	-1
	± 5	-2
I	± 46	73
J	± 13	-8
	± 11	-7
K	± 85	181
	± 65	95
L	± 8	6
M	± 8	9
	± 8	9
N	± 11	17
	± 10	12

165 Notes: \* data until 20<sup>th</sup> April 2010; <sup>#</sup> Transducer C had been set to finish on the original planned end date (30<sup>th</sup>  
 166 March 2010 – 69 days into test); <sup>+</sup> data became erratic after 14<sup>th</sup> April 2010. Prior to this, accuracy was  
 167 ± 11 mm; <sup>s</sup> data until 24<sup>th</sup> March 2010 when batteries failed; Transducer O used as a barometric transducer to  
 168 correct Transducer G.

169 Many of these peaks in atmospheric pressure variation are associated with temperature  
 170 extremes or rapid temperature changes. The largest peak corresponds with the transducers  
 171 being moved from a temperature controlled room (c. 20 °C) into the ambient air temperature  
 172 within the same building (c. 10 °C) on day 7. When barometric Transducers Q and S are  
 173 removed, the atmospheric pressure variation in the remaining subset is both less and more  
 174 stable (Figure 5). This indicates that transducers Q and S may be adversely affected by air  
 175 temperature fluctuations. Interestingly, the submersible versions of Transducer Q

176 (Transducers I, J, K) and S (Transducer N) also performed poorly in the laboratory  
177 temperature compensation test.

178 To demonstrate the effect of poor barometric compensation, the absolute Transducer N was  
179 corrected using both Transducer S (same brand) and Transducer P (Figure 6). Performance is  
180 greatly improved by correction with Transducer P, with the accuracy increasing from  $\pm 10$   
181 mm to  $\pm 6$  mm with considerably less noise present.

## 182 CONCLUSIONS

183 Fourteen leading brands of pressure transducer commonly deployed in hydrogeological and  
184 hydrological studies were tested under laboratory and field conditions to highlight how  
185 performance can vary under similar environmental conditions. Under the shorter, more  
186 controlled laboratory tests, sensor accuracy was generally to within specifications. Precision  
187 was less than  $\pm 7.3$  mm and under  $\pm 1.5$  mm for ten out of the twelve models lower pressure  
188 range transducers tested. Poor temperature compensation was the most significant outcome of  
189 the laboratory testing and five of the absolute sensors performance were substandard.

190 Field test results showed accuracy was generally to within around  $\pm 10$  mm. Drift was notable  
191 on many of the sensors and varied between negligible and 27 mm for lower pressure range  
192 models. This appeared to be of linear or curved forms in some cases. Crucially drift is not  
193 often cited in product specifications, but may be the key accuracy determinant during long-  
194 term water level monitoring. Variations in pressure recorded by some of the barometric  
195 transducers were also noteworthy. This was most evident during extreme temperatures or  
196 during rapid temperature changes. The diverse performance of the various transducers under  
197 test conditions may be a result of transducer design and internal correction algorithms, but  
198 also importantly the thoroughness of the calibration process which differs between  
199 manufacturers.

200 An industry-wide standard for calibration and specification would eliminate uncertainty  
201 surrounding the procedures currently undertaken and lead to greater transparency for the  
202 customer. This would allow better informed selection of equipment to suit different user  
203 needs and provide users with an improved understanding of product performance.  
204 Manufacturers would also be able to define clear transparent niches for marketing individual  
205 products.

206 Furthermore, it is imperative that any future standard addresses sensor drift which would  
207 ideally be based on field data. This will become increasingly important as water practitioners  
208 move towards more automated solutions for water level monitoring and site visits become  
209 less frequent.

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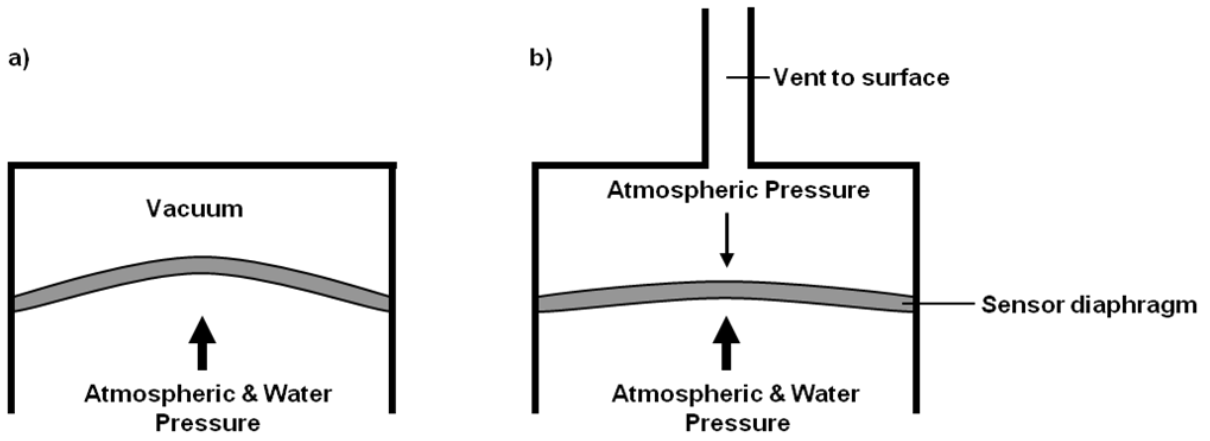
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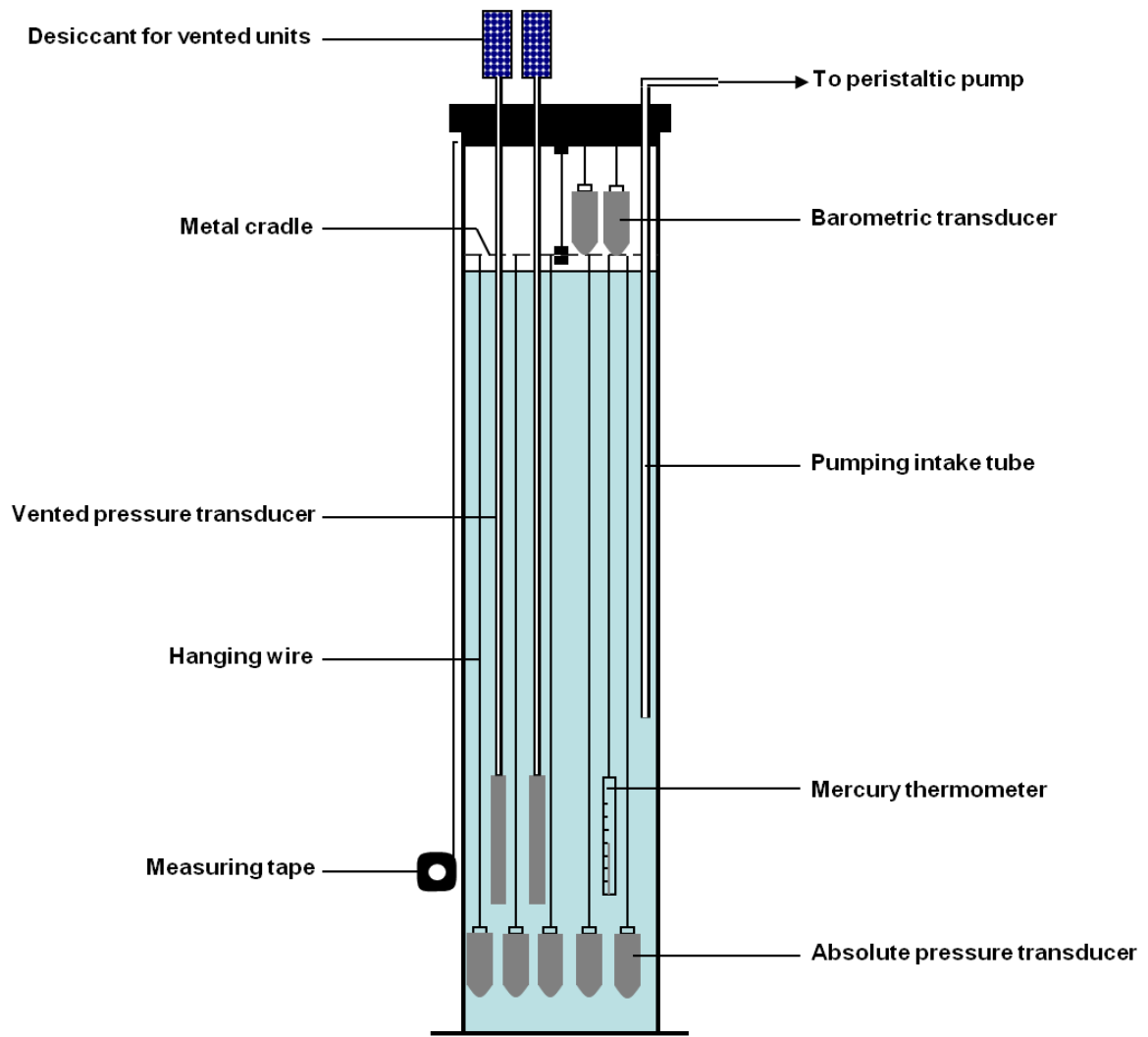
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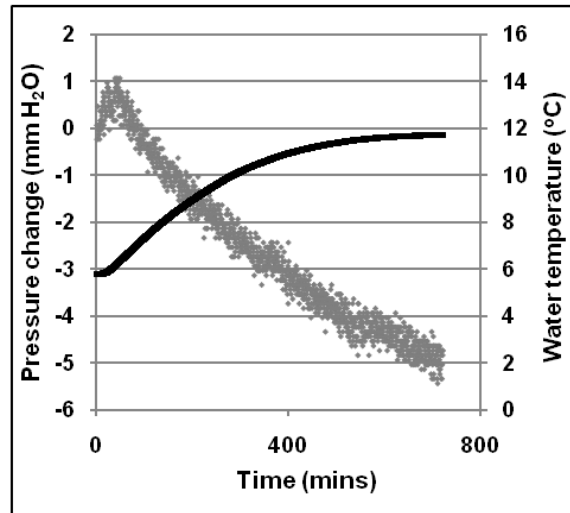
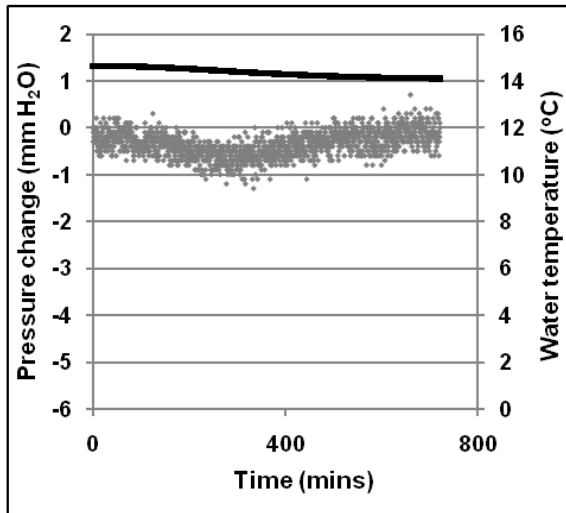


261 Figure 1 Comparison of absolute (a) and gauged (b) pressure transducers



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263 Figure 2 The experimental test bed

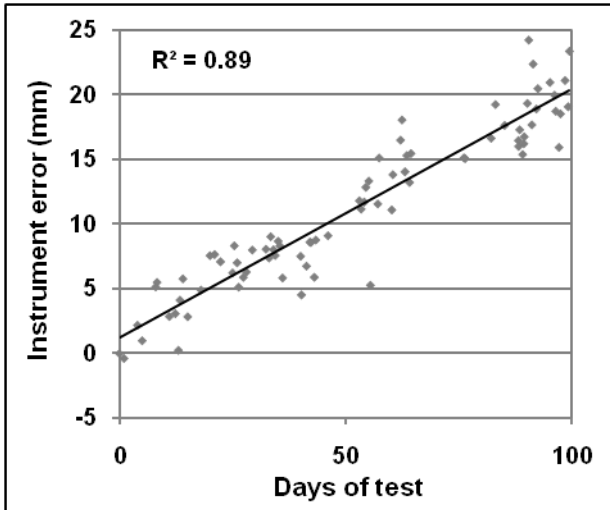


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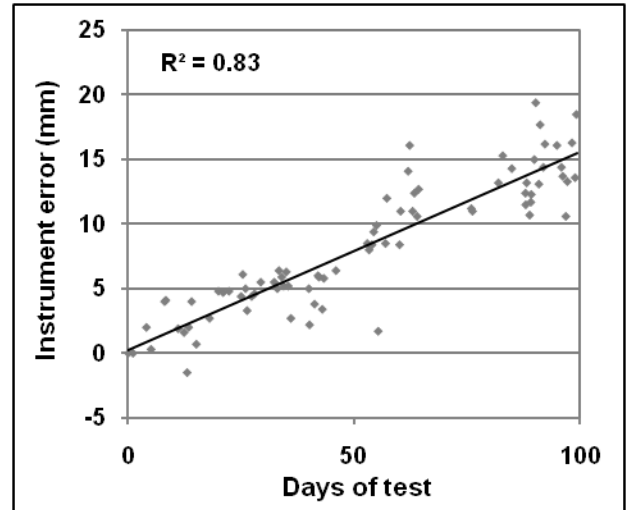
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264 Figure 3 (a) precision test and (b) temperature compensation test on Transducer N;  
 265 temperature – black, pressure – grey

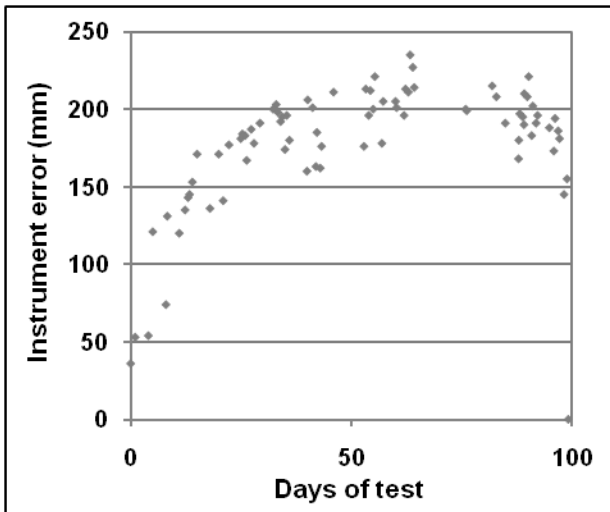
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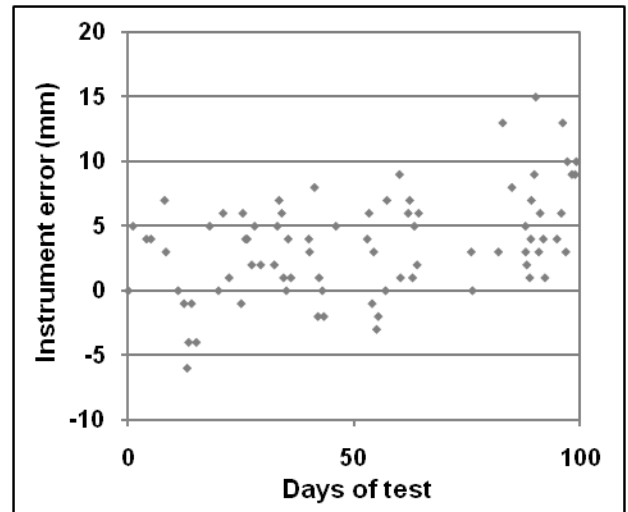
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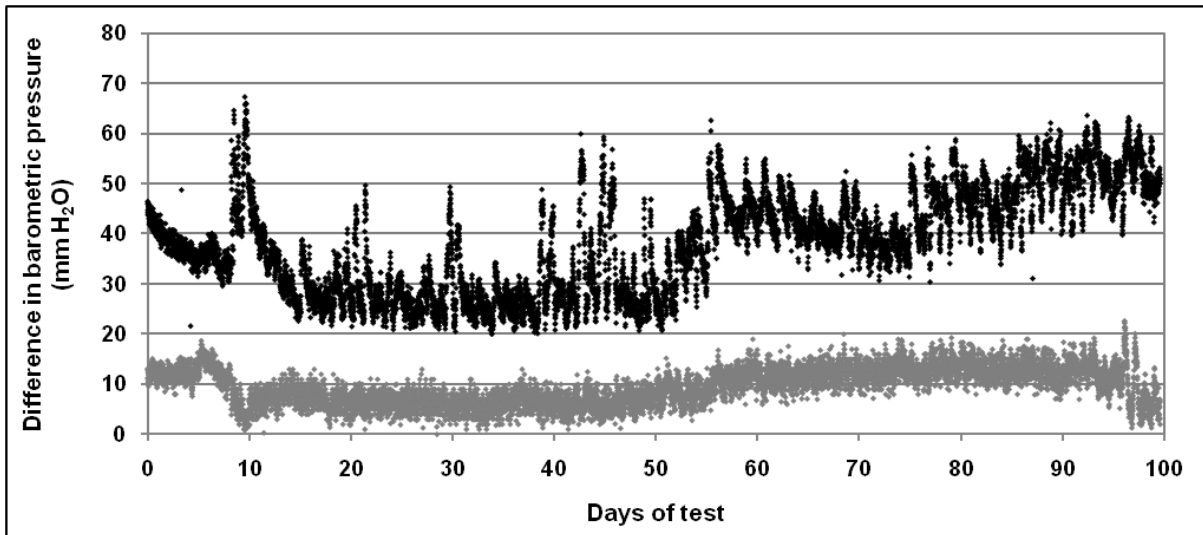


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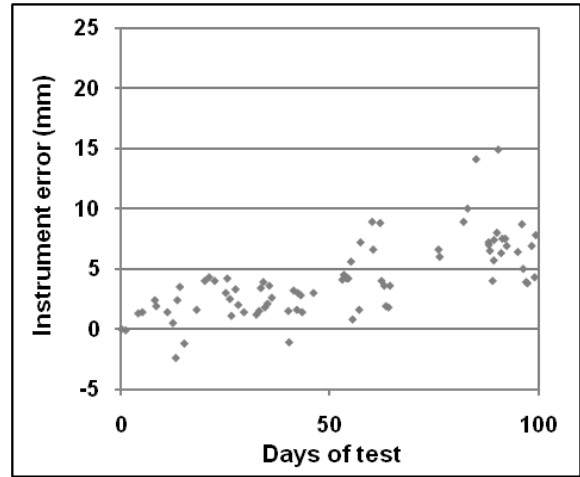
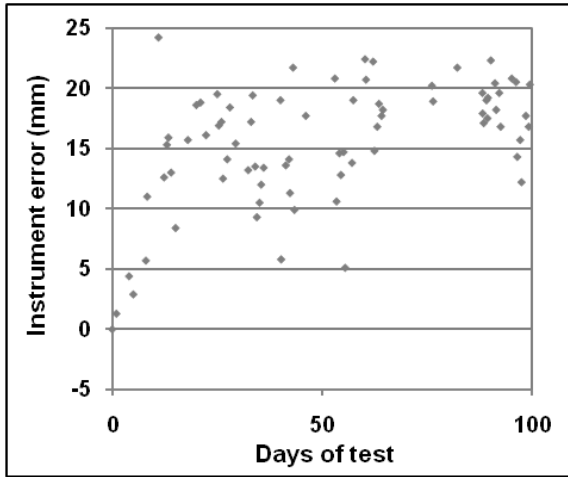
267 Figure 4 Examples of instrument error over time (a) Transducer B (b) Transducer A (c)  
 268 Transducer K (d) Transducer M



269

270 Figure 5 Variation in pressure recorded by all five barometric pressure transducers (black)  
271 and solely O, P and R (grey)

272



a)

b)

Figure 6 - Highlighting the issue of poor barometric compensation of water level data with Transducer N compensated with (a) Transducer S (same brand) (b) Transducer P