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

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ABSTRACT

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

INTRODUCTION

Pressure transducers are widely used in hydrogeological and hydrological sciences for monitoring water levels. The technology converts an applied fluid pressure, generally across a sensor diaphragm, to an electrical signal and then to an actual pressure. This assumes a water density, which is generally estimated from the measured water temperature and an in-built compensation algorithm. The effects of water salinity can also be addressed, but it is normally assumed to be constant during continuous measurements.

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

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

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

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

TEST METHODOLOGY

Fourteen different leading brand models of submersible pressure transducers were tested. Six were vented and the remainder were absolute (Table 1). Generally, sensors were low pressure range models (less than 15 m H_2O), although one was 30 m H_2O range and one was 100 m H_2O range. Five different barometric transducer units were also tested. Where possible, two of each submersible sensor was tested to ensure repeatability.

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

The test bed was located in a temperature controlled laboratory in order to minimise the external influence of atmospheric temperature on the water column, which could otherwise result in small head changes. Provisional testing showed that daily water column temperature variations were under 1^{o}C in this laboratory. Prior to any testing, the column was filled at least one week in advance to allow the water temperature to equilibrate. A mercury thermometer was also placed in the tube to manually monitor water temperature.

Table 1 - Transducers tested

Transducer	No. tested	Type	Range ($m\ H_2O$)
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

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

Transducer accuracies were evaluated by lowering the water level by a sequence of set steps (10, 20, 50, 200, 1000 mm) and comparing against measured level changes. Each step change was held for a total of 90 minutes, including 30 minutes for sensors to equilibrate. All instruments were set to log at 30 second intervals. Step changes recorded by each sensor were calculated as the average of 120 pressure readings following the equilibration period. The total error associated with two manual readings of the Class I measuring tape at the beginning and end of each step change was assumed to be 1 mm.

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

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

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

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

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

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

RESULTS & DISCUSSION

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

All but two of the sensors (Transducer A and one of Transducer L) achieved their product accuracy specification. No errors could be detected in two of the vented and one of the absolute sensors. Precision results were varied and ranged from 0.4 to 74.2 mm, although the lower pressure range sensors ranged between ± 0.4 and ± 7.3 mm. Excluding two of the models, precision was consistently under ± 1.5 mm for the lower pressure range transducers.

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

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

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

It is noted that the estimated drift will inherently also take sensor accuracy into account. Moreover, drift may differ significantly between locations as a result of the geochemical and hydrogeological setting. In the test locality, iron biofilms and calcite scaling could have caused an issue with some sensors. Movement of the hanging cables can also not be ruled out completely, although there are no apparent sudden increases in instrument error.

Over the first 24 hours of the field test the five barometric transducers ranged by an average of 43 mm H_2O, or 21 mm H_2O when not including Transducer Q. This represents a significant difference in pressure. Moreover, the difference between transducers varied over time, and reached as much as 67.4 mm (Figure 5).

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 (^{o}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^{+}	-	-	-	-	-	± 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$^{\#}$
	-	-	-	-	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^{+}	-	-	-	-	-	± 4.5	2.6	± 5.8	N

Notes: dash denotes a mean error of less than 2 mm; $^{+}$ data compensated with barometric Transducer P; * results of only one precision experiment; $^{\#}$ classed as technically 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.

Table 3 Results of field testing on pressure transducers

Transducer	**Field accuracy (mm)**	**Estimated drift (mm)**
A	± 9	12
	± 10	14
B	± 22[+]	15
	± 12	19
C	± 8[#]	13[#]
	± 9[#]	13[#]
D	± 9	10
E	± 27	27
	± 28[$]	27[$]
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

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

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

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

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

CONCLUSIONS

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

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

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

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

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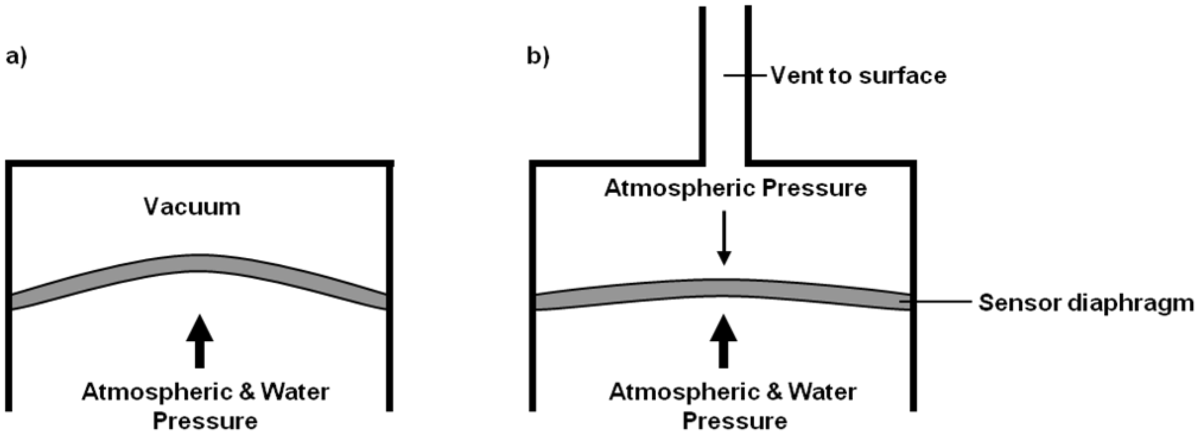


Figure 1 Comparison of absolute (a) and gauged (b) pressure transducers

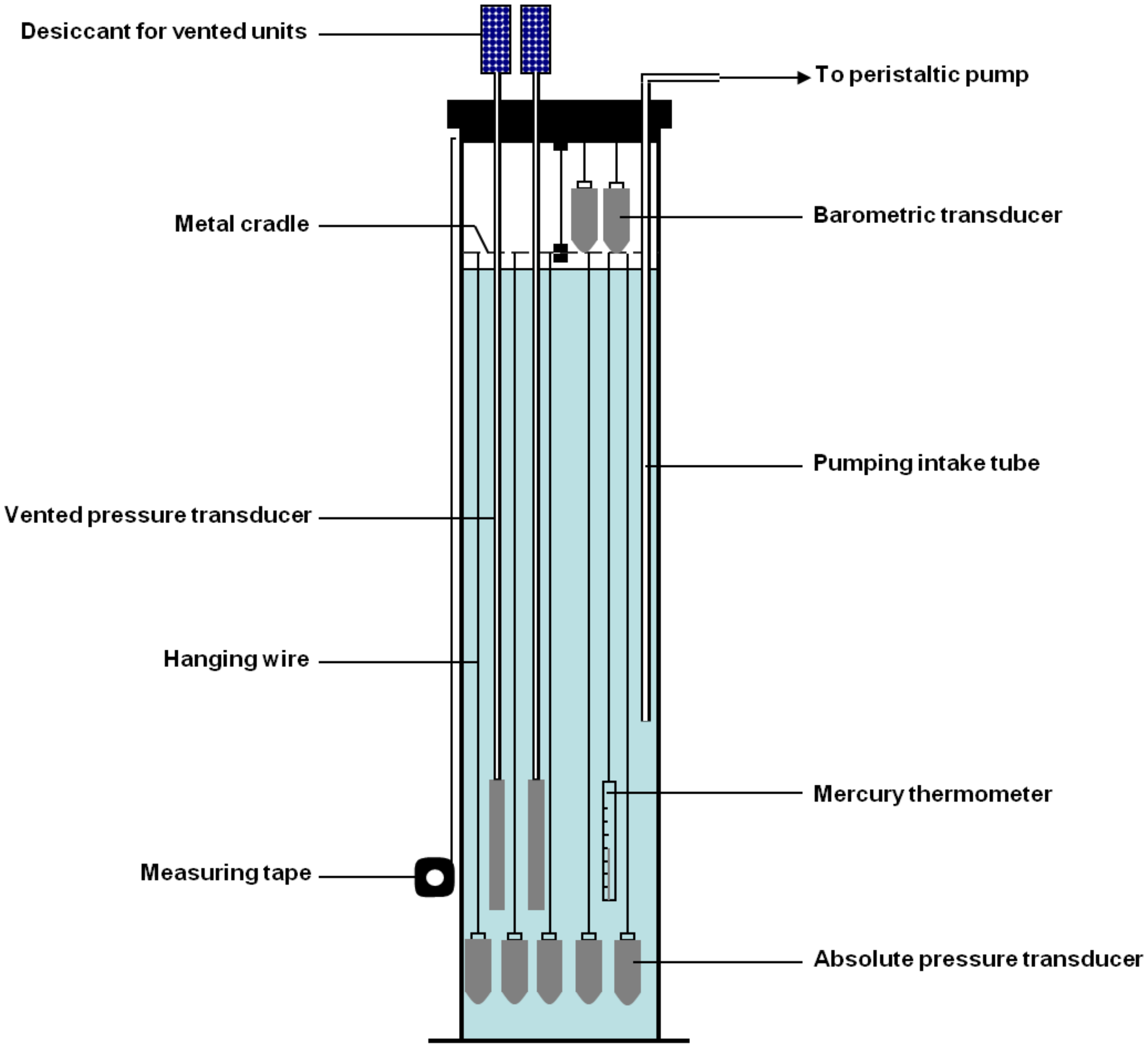
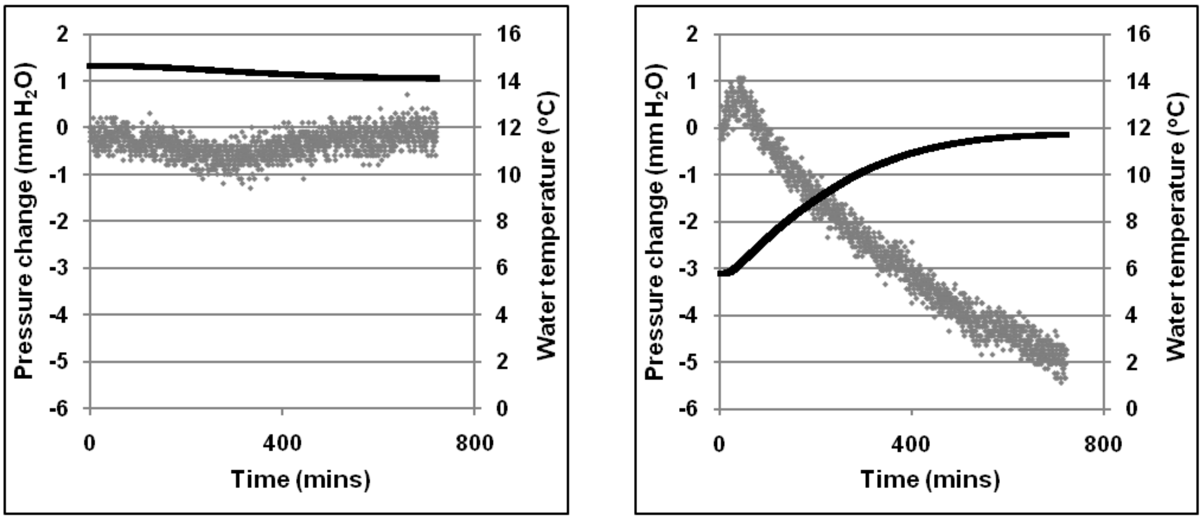
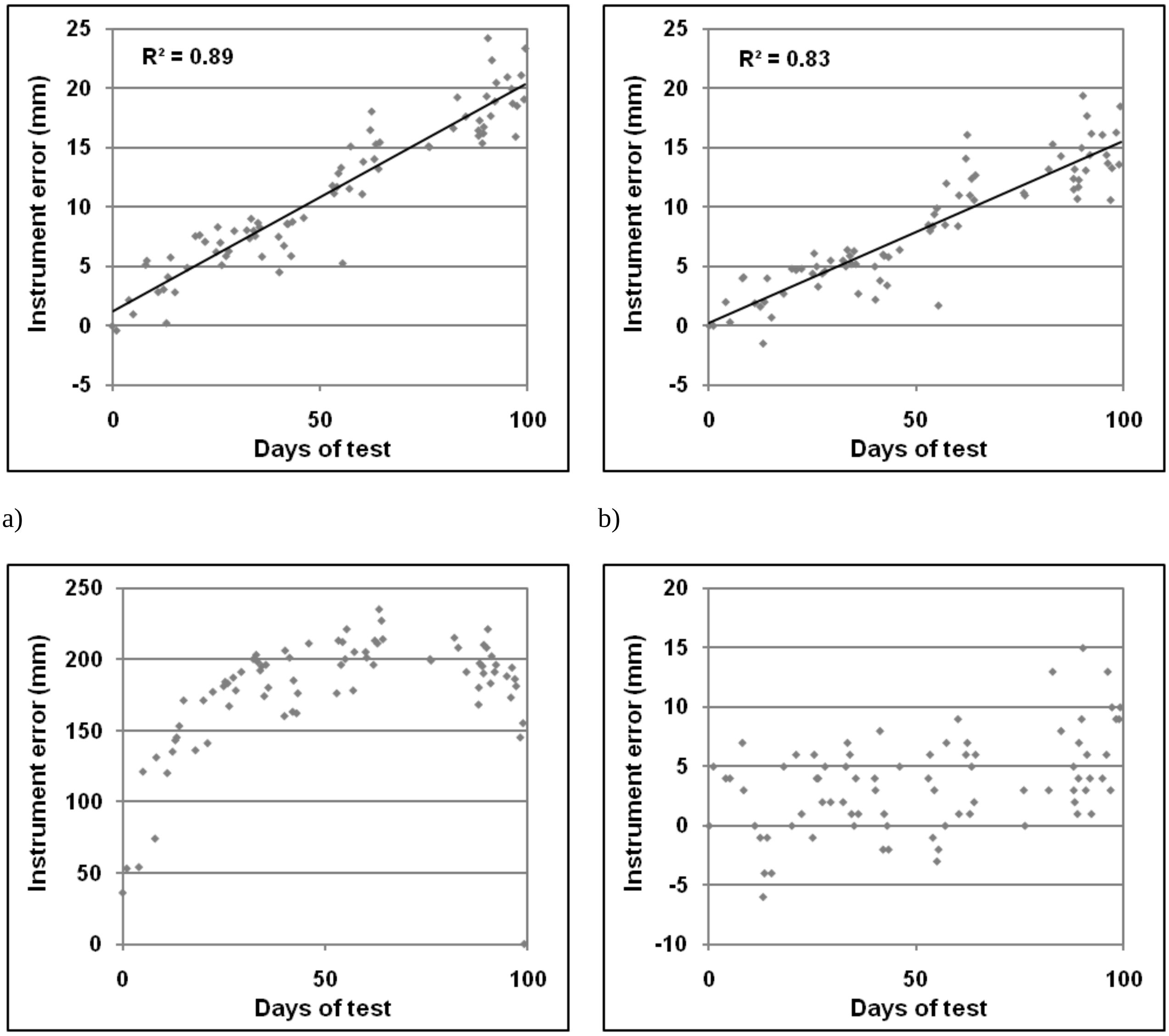


Figure 2 The experimental test bed



a) b)

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



a)

b)

c)

d)

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

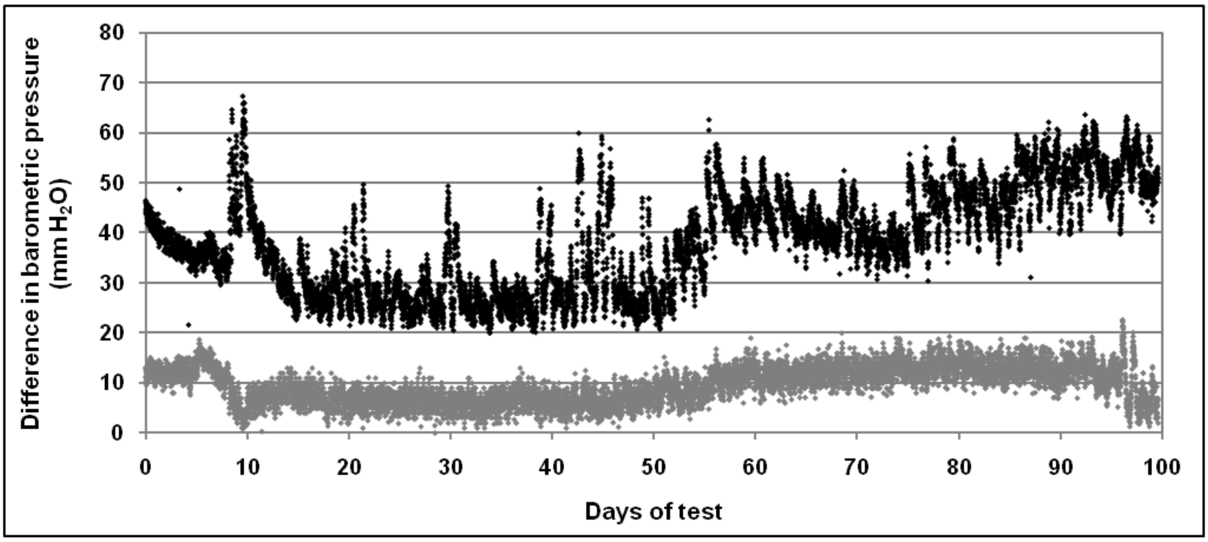
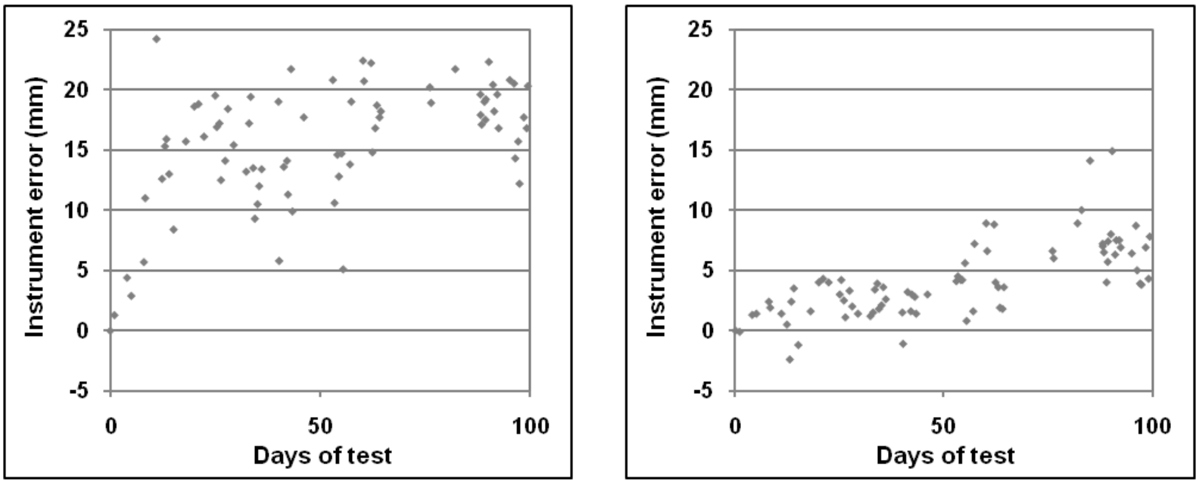


Figure 5 Variation in pressure recorded by all five barometric pressure transducers (black) and solely O, P and R (grey)



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