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Technical performance of selected pressure transducers used for groundwater monitoring under laboratory and field conditions

Groundwater Science Programme

Open Report OR/10/060

BRITISH GEOLOGICAL SURVEY

GROUNDWATER SCIENCE PROGRAMME

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Technical performance of selected pressure transducers used for groundwater monitoring under laboratory and field conditions

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Keywords

Pressure transducers, groundwater monitoring, sensor drift, accuracy, precision

Bibliographical reference

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) on the performance of pressure transducers commonly used in groundwater investigations.

Acknowledgements

The authors are grateful to Barry Townsend (BGS) who undertook the majority of the field measurements and assisted with work in the BGS Hydrogeological Properties and Processes Laboratory in Wallingford. Additionally, we are grateful for the equipment that was kindly loaned to us by various European and North American manufacturers and suppliers.

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Summary

Over recent years the British Geological Survey (BGS) has been involved with research on shallow groundwater systems using a limited range of pressure transducers to monitor groundwater level and temperature. However, there have been concerns regarding their accuracy, precision, electronic drift and temperature compensation, which have limited data interpretation in some cases.

This study aimed to evaluate technically the existing range of pressure transducers held by the BGS Groundwater Science Programme against a range of alternative commercially available transducers, sourced from previously unused manufacturers/suppliers. Laboratory testing included accuracy, precision and temperature compensation assessments. Field testing involved deploying all instruments in an on-site borehole for 99 days. Sensor readings were compared against frequent dip measurements to assess instrument field accuracy and potential drift.

Laboratory accuracy tests indicated the majority of sensors performed within the product specification. The most accurate units were considered to be Transducers B, C, G and O which recorded all water level changes to within the experimental error. Precision was generally under ± 1.5 mm, with the exception of Transducers I to M and Transducers G and O which ranged between ± 3.6 and 74.2 mm. Temperature compensation was regarded as a concern on Transducer G, I, J, K and N.

Field accuracy was generally to within around ± 10 mm, with the exception of the higher range models. Some sensors also clearly demonstrated decreasing accuracy over time, i.e. drift. This appeared to be of linear or curved forms in some transducers, although was not clearly identifiable in many others. The most accurate sensors, and inherently those with the least drift, were absolute Transducer H and vented Transducer F.

1 Introduction

1.1 PRESSURE TRANSDUCERS

1.1.1 Technology background

Pressure transducers provide an easy and accurate way to monitor groundwater levels. They can be used to examine natural level fluctuations at a variety of timescales and can also record responses to induced stresses, e.g. during aquifer pumping tests. Additionally, they can record water temperature, which can be a useful natural tracer in groundwater-surface water interaction studies (Constantz, 2008).

The technology is based upon converting an applied fluid pressure, generally across a sensor diaphragm, to an electrical signal. This is, in turn, translated to an actual pressure. The conversion is based on a water density of 1 kg/l, i.e. pure water at 4^{o}C, for submersible loggers. Nevertheless, many sensors also monitor water temperature. Consequently they are able to perform continuous automatic temperature compensation on pressure readings over a specific calibrated range to ensure greater accuracy. The effects of water salinity can also be addressed, but it is typically assumed to be constant during continuous measurements. Barometric pressure transducers generally also compensate for temperature to ensure greater accuracy.

1.1.2 Types of transducer

There are two main types of submersible pressure transducer for measuring water levels: absolute (non-vented) or gauged (vented) (Figure 1.1). An absolute device records the combined atmospheric pressure and pressure exerted by the overlying water column depth. Therefore, the data has to be corrected using a separate record of atmospheric pressure – usually data collected with a barometric pressure transducer. Gauged transducers are vented to the surface eliminating the effects of atmospheric pressure across the sensor diaphragm and, thus, solely recording the pressure exerted by the overlying water column.

Transducers can have in-built data loggers or require connection to an external data logger located at the surface. External loggers usually require some form of borehole housing to provide sufficient secure space at the surface.

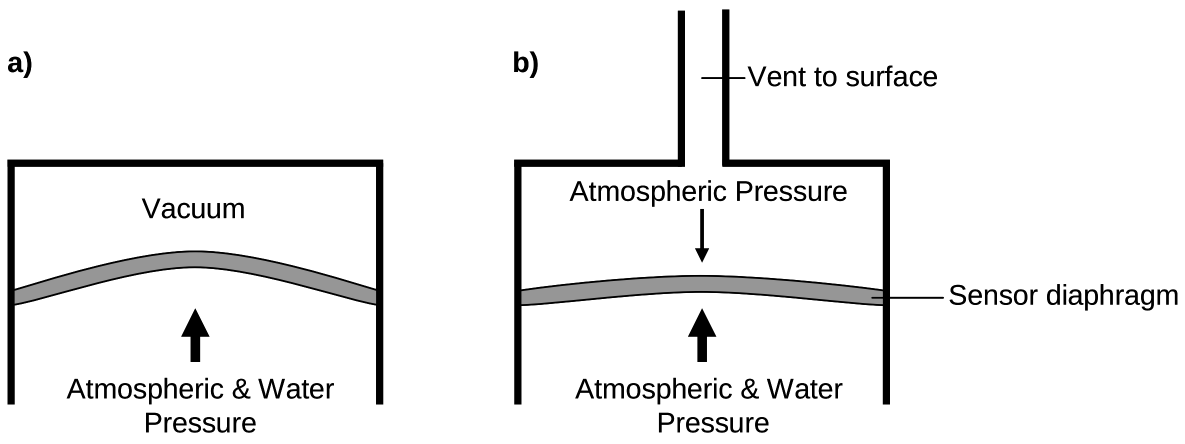


Figure 1.1 - Comparison of absolute (a) and gauged (b) pressure transducers

1.2 BACKGROUND TO THE STUDY

Over the last few years the British Geological Survey (BGS) Groundwater Science Programme has been heavily involved in research on shallow groundwater systems. This has focussed on groundwater-surface water interaction (Allen *et al.*, 2010), groundwater flooding (Macdonald *et al*., 2007) and coastal dune wetlands (Stratford *et al.*, in press). These ongoing projects require the accurate and precise measurement of groundwater and surface water levels to characterise small variations in hydraulic head. This has been traditionally undertaken using a limited range of pressure transducers. However, examination of the data has revealed uncertainty over their accuracy, precision, electronic drift and temperature compensation. This has significantly limited data interpretation in some cases.

Figure 1.2 collates typical examples of poor quality water level data retrieved in recent years. Figure 1.2a highlights the disparity between transducer data and dip measurements. Note the sensor data are referenced against the final dip measurement before the instrument was removed before downloading. The transducer was not disturbed between the start and end points. All dips were undertaken by the same individual, using the same dip tape, to the same reference point. The sensor is either inaccurately recording pressure changes or drifting over time.

Figure 1.2b identifies another common problem – lack of instrument precision or ‘noise’ in the data. In this example, the noise recorded by a new sensor (10 m H_2O range) is around 5 cm H_2O. The technical specifications for this absolute pressure instrument and barometric transducer used for compensation state accuracies of ± 1 cm and ± 0.5 cm, respectively. Therefore, the total expected noise should not exceed 3 cm in a worst-case scenario.

Figure 1.2c demonstrates the effects of ‘extreme’ temperatures on a barometric pressure transducer. These are deployed at research sites to barometrically compensate absolute pressure sensors. It is recommended that they are installed several metres below ground level where air temperature variations are subdued. However, where monitoring shallow, even artesian groundwaters, this may not be feasible. Consequently the barometric devices can become exposed to extreme temperatures. The data shown are from a groundwater-surface water research site, where both barometric sensors record unrealistically high atmospheric pressures (up to 1150 mbar) when the air temperature drops below 0^oC. This results in the erroneous sudden drops in the incorrectly compensated water level shown in Figure 1.2c.

This type of temperature dependent behaviour may be indicative of poor automatic temperature compensation. It is noted that the temperature compensation range for both these units at this site is $0\text{-}40^oC$. However, it could also be an external effect, e.g. freezing of condensation on sensor.

1.3 OBJECTIVE

The objective of this study was to evaluate technically the existing range of pressure transducers held by the BGS Groundwater Science Programme against a range of alternative commercially available transducers, sourced from previously unused manufacturers/suppliers, using a combination of laboratory and field tests. Consequently it would be possible to advise on the expected field performance of each instrument, which could inform future procurement.

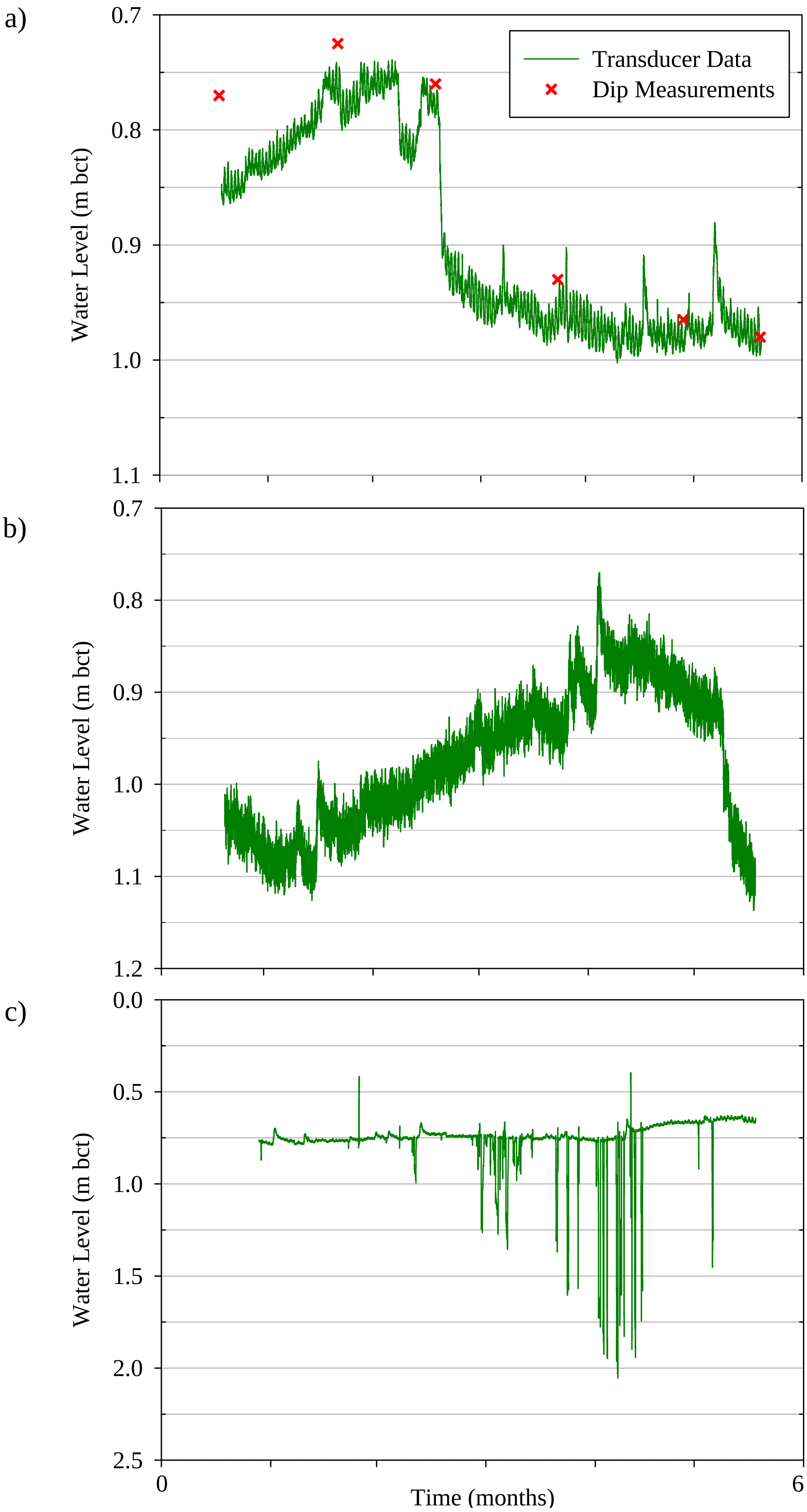


Figure 1.2 - Concerns with transducer a) accuracy and/or drift b) precision c) temperature compensation

2 Methodology

2.1 RANGE OF TRANSDUCERS

A total of 14 different models of submersible pressure transducers were available for testing (Table 2.1). Generally sensors were low pressure range models (less than 15 m H_2O), although Transducer I was 30 m H_2O range and Transducer K was 100 m H_2O range. Available sensors were retrieved from the existing stock of BGS sensors. The remaining transducers were sourced from manufacturers for evaluation on a 'free of charge' loan basis. Where possible, two of each sensor were tested to ensure repeatability. Five different barometric units were also available (Transducers O to S). Additionally a capacitance level probe was included as an economical alternative form of technology.

Table 2.1 - Transducers available for testing

Sensor	Number	Type
Transducer A	2	Vented
Transducer B	2	Vented
Transducer C	2	Vented
Transducer D	2	Vented
Transducer E	2	Vented
Transducer F [1]	2	Vented
Transducer G	1	Absolute
Transducer H	2	Absolute
Transducer I	1	Absolute
Transducer J	2	Absolute
Transducer K	2	Absolute
Transducer L	2	Absolute
Transducer M	2	Absolute
Transducer N	2	Absolute
Transducer O	1	Absolute or Barometric
Transducer P	1	Barometric
Transducer Q	1	Barometric
Transducer R	1	Barometric
Transducer S	1	Barometric
Capacitance sensor	2	Capacitance

Notes: [1] Campbell Scientific CR10 external logger used.

2.2 LABORATORY TESTING

2.2.1 Experimental test bed

An experimental test bed was established 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 (15 litres when full) (Figure 2.1). 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 level 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 monitor water temperature manually.

A peristaltic pump was installed to allow water to be introduced and removed from the test bed 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 following metre.

2.2.2 Accuracy assessment

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.

2.2.3 Precision assessment

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.

2.2.4 Temperature compensation

The accuracy of temperature compensation of 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. This increase in temperature would have altered the fluid density and consequently the height of water in the column; although no significant level change should have been recorded by a pressure transducer, due to temperature compensation accounting for the shift in water density. Therefore, any instrument recorded variation in level should be very similar to variations recorded during the precision experiment, if temperature compensation is accurate.

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.

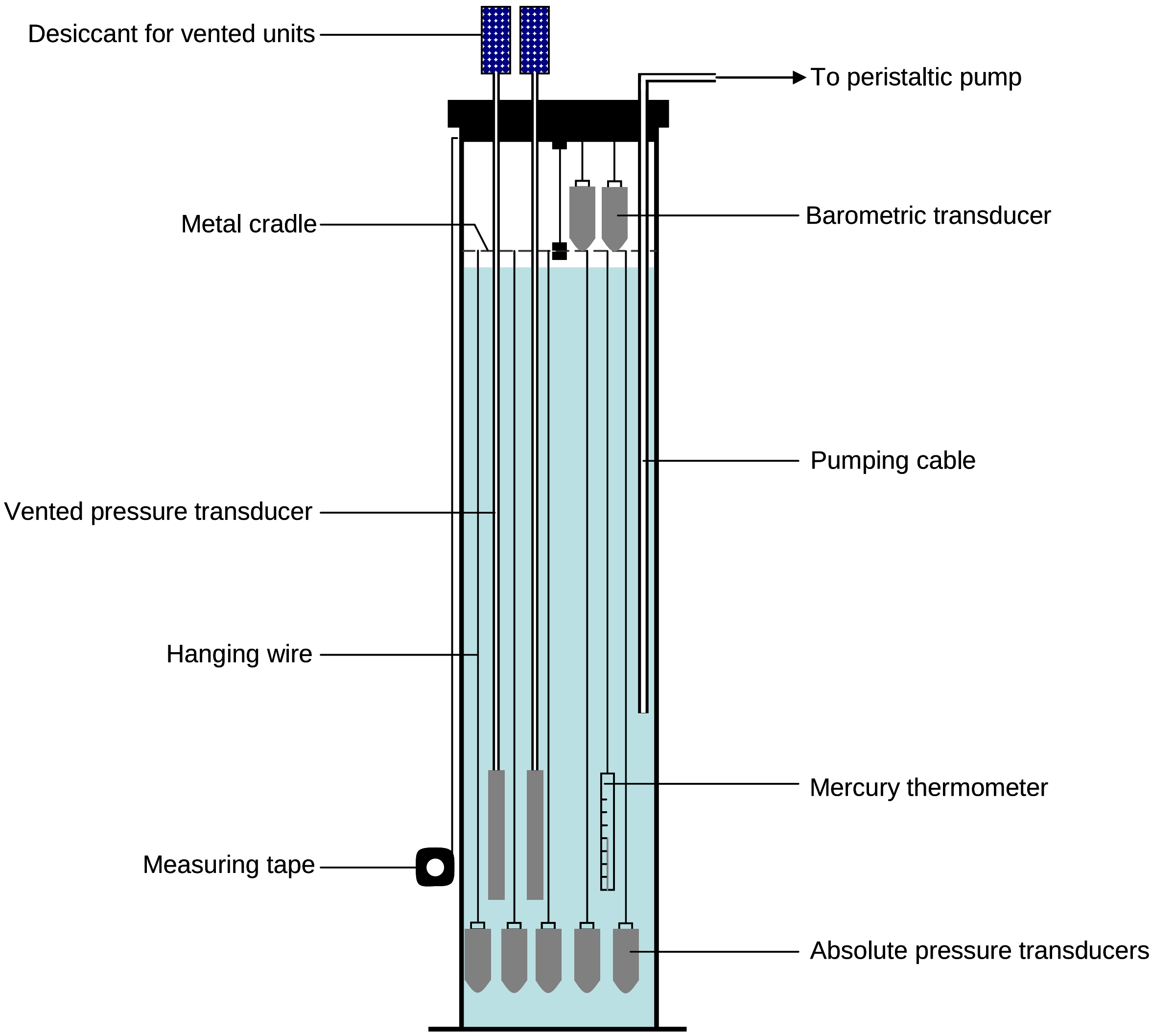


Figure 2.1 - Experimental test bed – total column height was 2 m

2.3 FIELD TESTING

2.3.1 Experimental borehole

In addition to the laboratory testing, it was essential to test the transducers in field conditions. The selected borehole was drilled to a depth of 53 m through River Terrace Deposits, the Glauconitic Marl Member, the entire thickness of the Upper Greensand Formation and into the Gault Clay Formation. The borehole is 200 mm in diameter: consisting of an inner 100 mm piezometer and the surrounding annulus both open to the Upper Greensand Formation. Non-vented sensors were installed in the piezometer and vented sensors were installed within the annulus.

The well is typically artesian and significantly affected by local abstraction. The shallow water table and daily fluctuations in the order of tens of centimetres were considered ideal for testing purposes.

2.3.2 Field procedure

All instruments were simultaneously installed in the secure borehole to similar depths (Figure 2.2). Barometric pressure transducers were deployed in a nearby building for security purposes, but at around the same elevation as the borehole cap. These sensors were initially in a temperature controlled room but were subsequently exposed to the ambient air temperature after 29th January 2010 at 15:00 hours. Submersible pressure transducers were left undisturbed in the borehole for 99 days. The borehole annulus was dipped to the nearest millimetre using the same Solinst dip tape, to the same reference point, on a regular basis. The dip tape was subsequently validated against a Class I measuring tape.

All sensors were set to log on a 15 minute interval and were referenced to the dip measurement at 09:30 on 21st January 2010; this was approximately 40 hours after all sensors were installed in the borehole. 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 when considering human error, but generally less than 3 mm.

Figure 2.2 – On-site testing borehole

3 Results & Discussion

3.1 LABORATORY TESTING

The results of the laboratory testing are summarised in Table 3.1. Full results are included in the appendices. 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.

3.1.1 Accuracy

Generally all sensors achieved their product specification. The exceptions to this are Transducer A and one version of Transducer L. No errors could be detected in Transducer B, Transducer C or Transducers G and O.

3.1.2 Precision

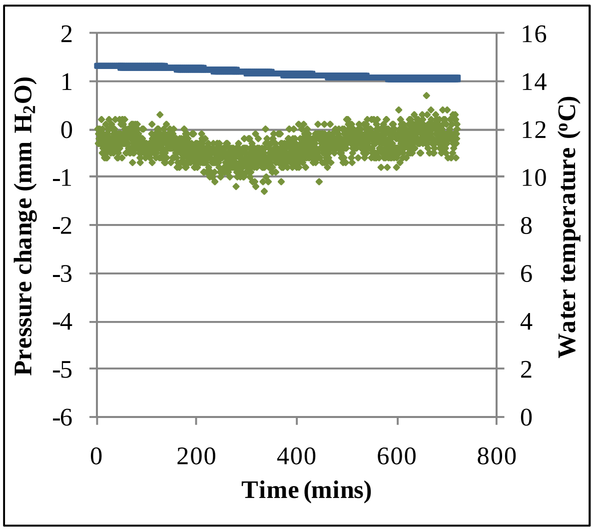
Precision results were extremely varied and ranged from 0.4 to 74.2 mm, although the majority varied between ± 0.4 and ± 7.3 mm. In fact with the exception of Transducers I to M and Transducers G and O, precision was always under ± 1.5 mm.

Precision appears to be influenced by the pressure range of the sensor. Additionally, vented transducers generally perform better than unvented transducers. The precision of Transducer D was limited by the milimetric resolution of the sensor. Transducer N was the most precise non-vented sensor.

3.1.3 Temperature Compensation

The results of the temperature compensation testing were regarded as significant for Transducers G, I, J, K, and N.

Figure 3.1 illustrates a pressure transducer with poor temperature compensation: during reasonably stable temperatures pressure readings are also stable; when water temperatures vary, pressure readings vary significantly.



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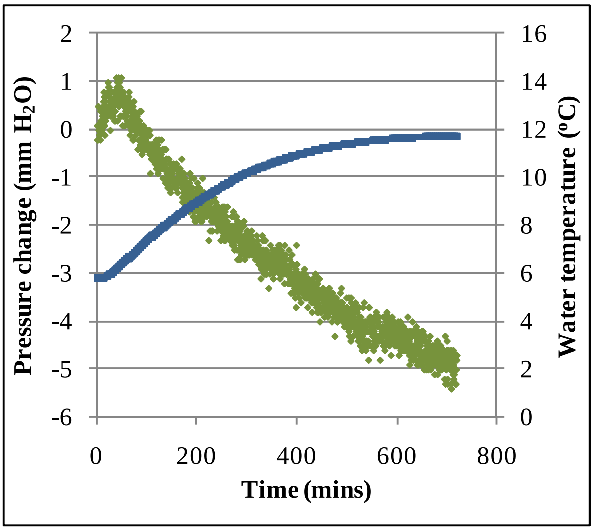


b)

Figure 3.1 - (a) Precision test and (b) temperature compensation test on Transducer N; temperature – blue, pressure – green.

Table 3.1 - Results of laboratory testing on pressure transducers

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

Note: + data compensated with Transducer P; * results of only one precision experiment; # classed as technically significant for the sensor but not for Transducer L, as particular sensor appears to be malfunctioning; Transducer E, Transducer F and capacitance level probe not tested.

3.2 FIELD TESTING

3.2.1 Field accuracy and sensor drift

The results of the field testing are summarised in Table 3.2. Full results are included in the appendices. 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 and Transducer E. The most accurate sensors were Transducers F and H. The capacitance level probe did not perform favourably against the pressure transducers.

It was also demonstrated that sensor accuracy deteriorated over time in many units, i.e. sensors drifted (Figure 3.2). 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 3.2). This was undertaken using the median of the final five instrument errors. 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; although it was not always completely evident (Figure 3.2).

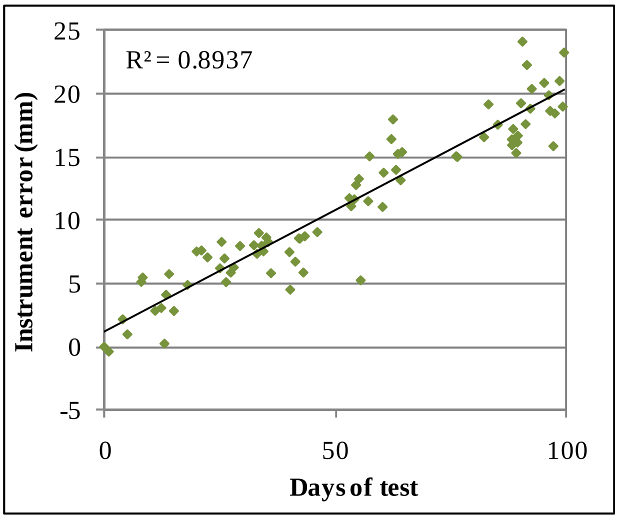
It is noted that the estimated drift will inherently also take sensor accuracy into account to a degree. Moreover, drift may differ significantly between locations as a result of the geochemical and hydrogeological setting. In this locality, iron biofilms and calcite scaling could have caused an issue 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.

Table 3.2 - Results of field testing on pressure transducers

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

Sensor	Field accuracy (mm)	Estimated drift (mm)
Transducer M	± 8	9
	± 8	9
Transducer N	± 11	17
	± 10	12
Capacitance level probe	± 117	-
	± 160	-

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.



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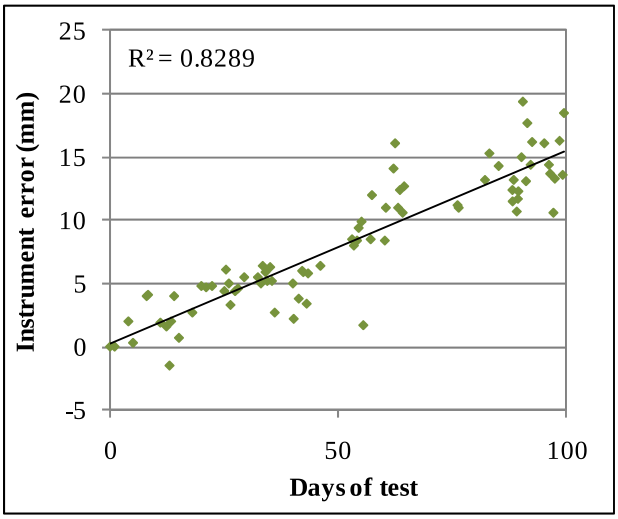

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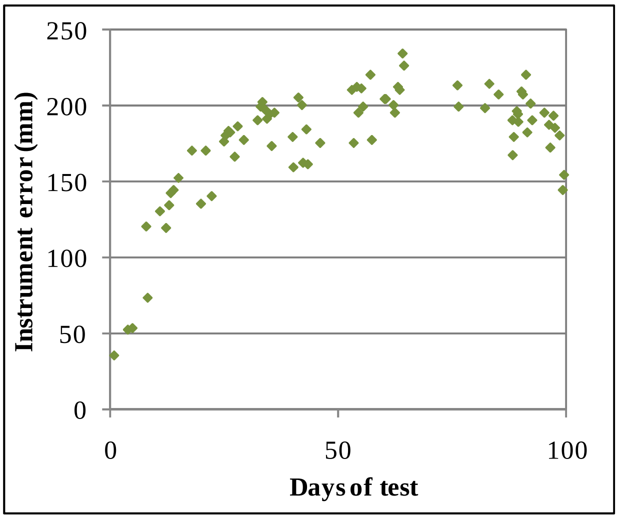

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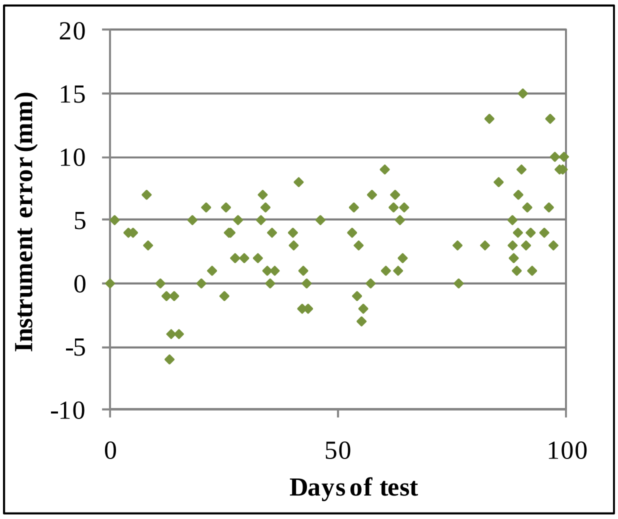


d)

Figure 3.2 - Examples of instrument error over time (a) Transducer B (b) Transducer A (c) Transducer K (d) Transducer M

3.2.2 Performance of barometric pressure transducers

Over the first 24 hours of testing 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 quite a difference in pressure when considering the accuracy results above. Moreover, the difference between transducers varied over time, and reached as much as 67.4 mm (Figure 3.3).

Many of these peaks in the pressure range can be attributed to temperature extremes or rapid temperature changes. The largest peak corresponds with the transducers being moved from a temperature controlled room (c. 20 ^{o}C) into the ambient air temperature (c. 10 ^{o}C) on day 7. When Transducers Q and S are removed from the comparison, then atmospheric pressure variation is both smaller and less spiky (Figure 3.4). This indicates that both these transducers may be adversely affected by air temperature fluctuations and thus should not be installed near the ground surface. Interestingly the submersible versions of Transducer Q (Transducers I, J, K) and S (Transducer N) also performed poorly in the laboratory temperature compensation test.

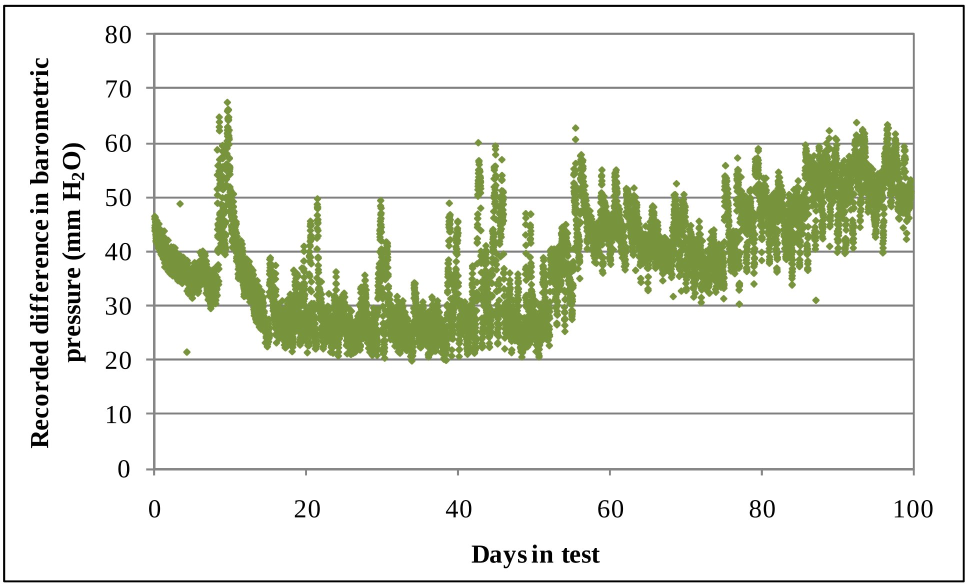


Figure 3.3 - Variation in pressure recorded by all five barometric pressure transducers

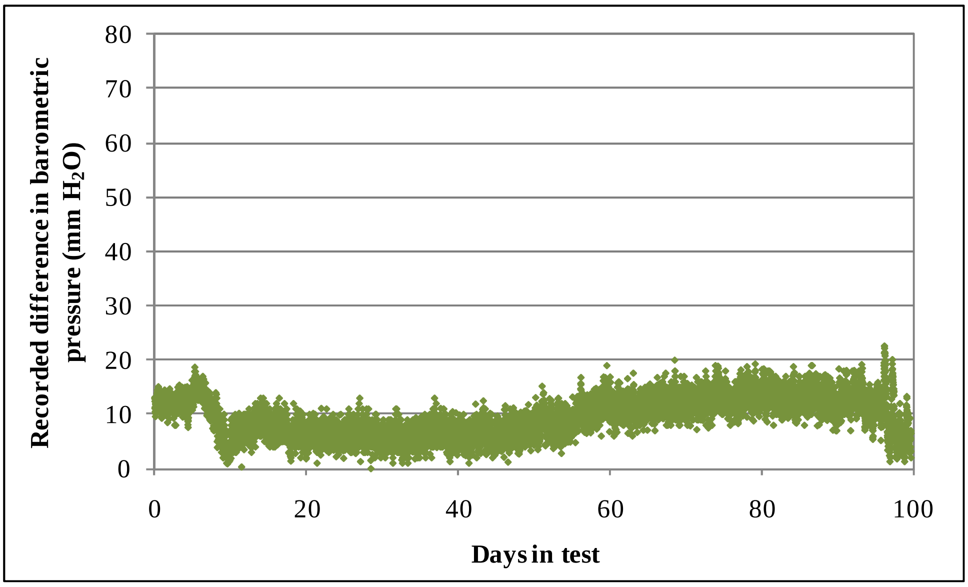
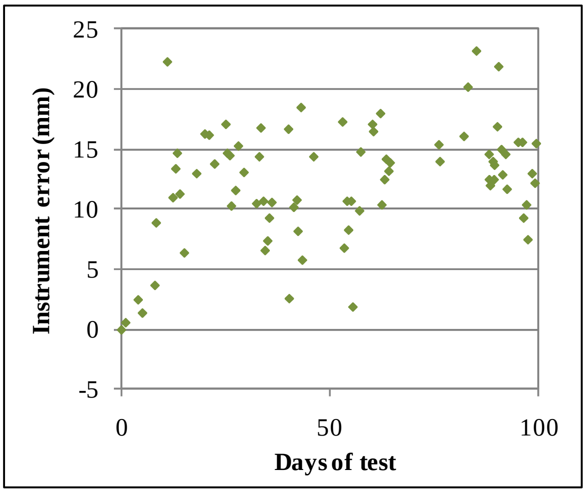


Figure 3.4 - Variation in atmospheric pressure recorded by Transducers O, P and R

To demonstrate the effect of poor barometric compensation, the absolute Transducer N was corrected using both Transducer S (same brand) and Transducer P (Figure 3.5). It is clear that performance is greatly improved by correction with Transducer P, with the accuracy increasing from ± 10 mm to ± 6 mm and considerably less noise present.



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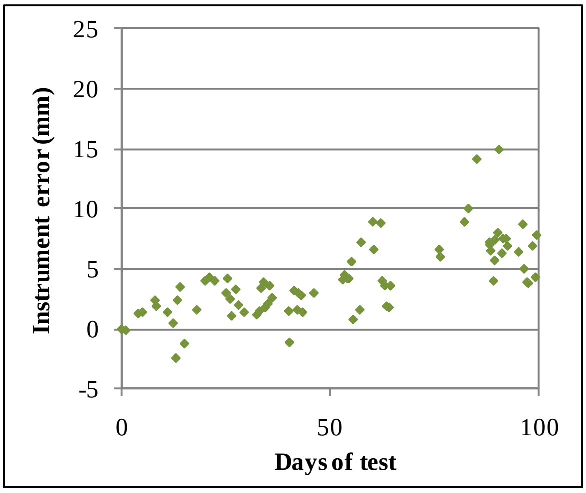

b)

Figure 3.5 - Highlighting the issue of poor barometric compensation of water level data with Transducer N compensated with (a) Transducer S (same brand) (b) Transducer P

4 Conclusions

A range of the BGS Groundwater Science Programme's and several other commercially available pressure transducers have been tested under laboratory and field conditions. Sensor accuracy, precision and accuracy of temperature compensation have been reported under controlled conditions in the laboratory:

- Sensor accuracy was generally within product specification. The most accurate units were considered to be Transducers B, C, G and O which recorded all water level changes to within the experimental error.
- Precision was generally under ± 1.5 mm, with the exception of Transducers I to M and Transducers G and O.
- Temperature compensation was regarded as a concern on Transducers G, I, J, K and N.

Field accuracy and sensor drift was also examined over a period of 99 days. Field accuracy was generally to within around ± 10 mm, with the exception of the higher range models. The capacitance water level probes did not perform favourably against the pressure transducers and were only accurate to within ± 117 and ± 160 mm.

Some sensors also clearly demonstrated decreasing accuracy over time, i.e. drift. This appeared to be of linear or curved forms in some transducers, although was not clearly identifiable in many others. There were also concerns with some barometric pressure transducers - Q and S both appeared to be adversely affected by fluctuating air temperatures. The most accurate sensors in the field, and inherently those with the least drift, were absolute Transducer H and vented Transducer F.

References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

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Appendix A – Results of Transducer A

<u>Sensor 1</u>

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	0.1	0.2	0.7	0.1	7.0
	Test 2	0.1	0.2	0.2	0.7	7.4
	Average	*0.1*	*0.2*	*0.4*	*0.4*	*7.2*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 0.5	0.7
2	± 0.9	1.1
Average	*± 0.7*	*0.9*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 0.3	7.3	N

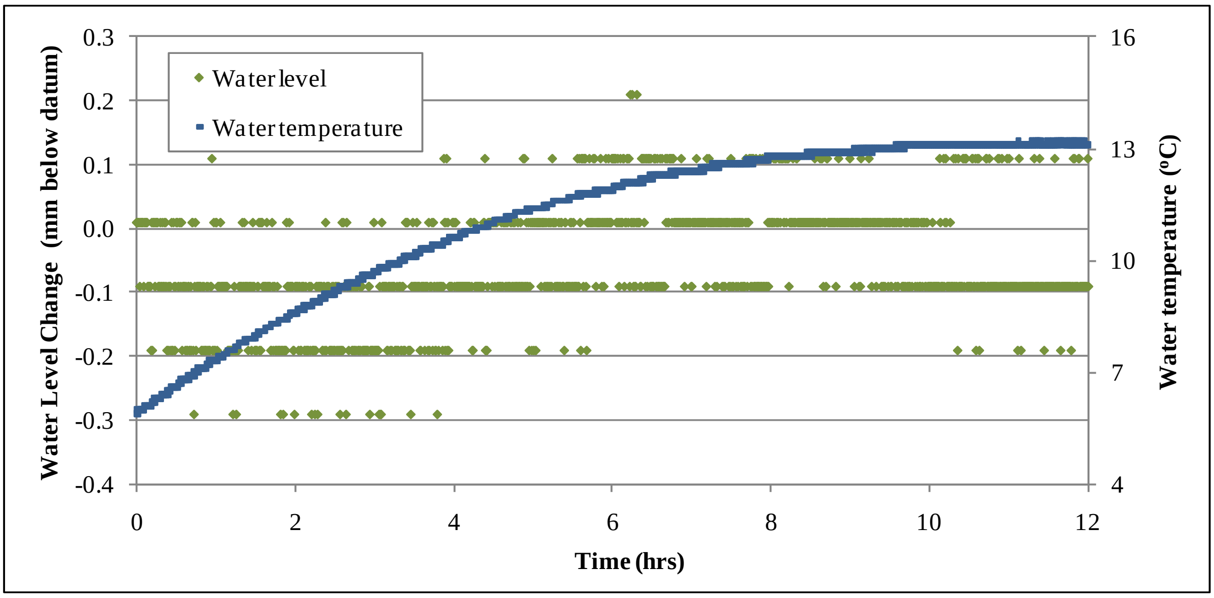

Figure 1 - Results of temperature compensation test

2. Field Results

Sensor appears to drift linearly throughout test period

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 9	12

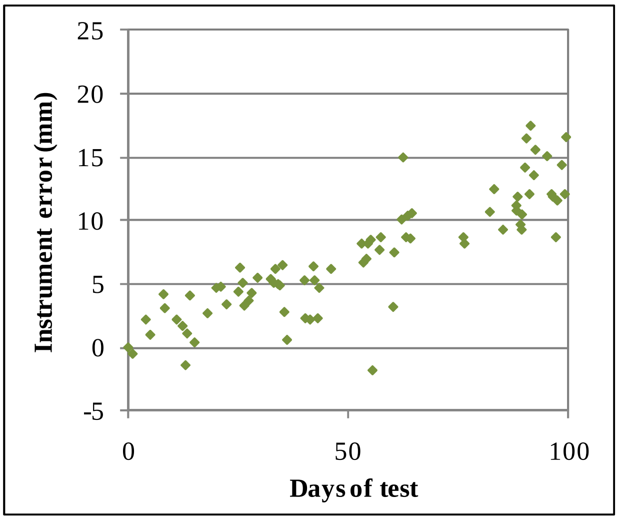

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Sensor 2

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	0.1	0.3	0.6	0.4	5.6
	Test 2	0.1	0.1	0.3	0.6	6.9
	Average	*0.1*	*0.2*	*0.4*	*0.5*	*6.2*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 0.3	0.7
2	± 1.0	1.0
Average	*± 0.7*	*0.8*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 2.6	6.7	N

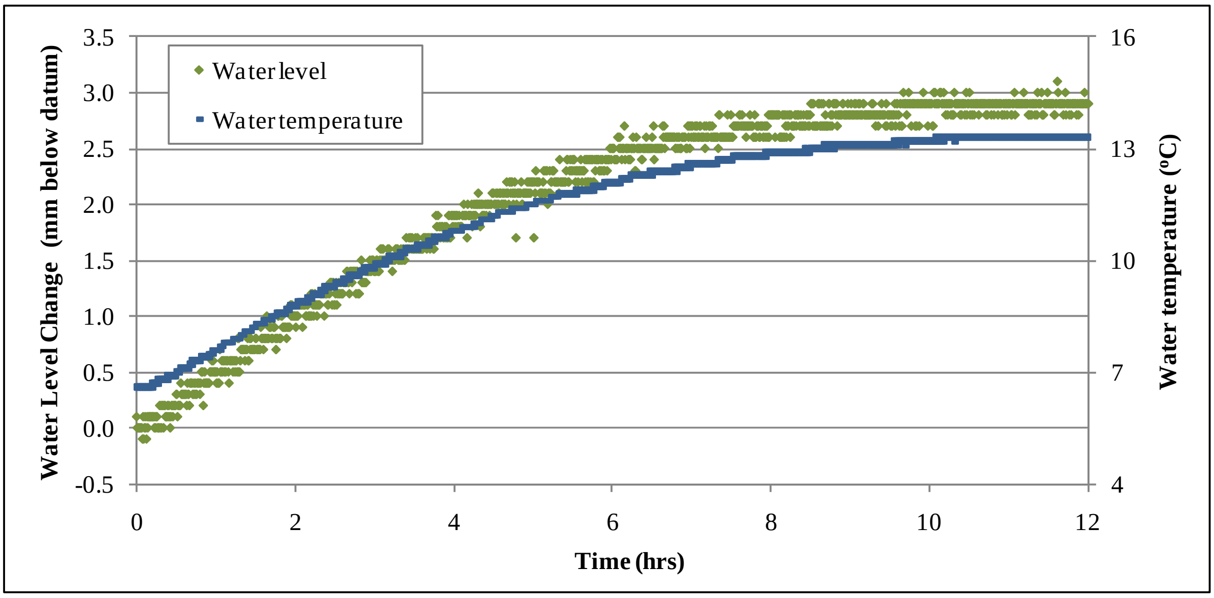

Figure 1 - Results of temperature compensation test

2. Field Results

Sensor appears to drift linearly throughout test period.

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 10	14

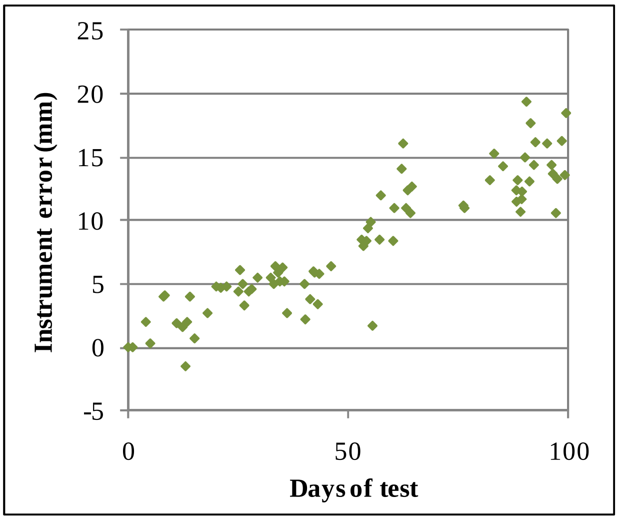

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Appendix B – Results of Transducer B

Sensor 1

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	0.2	0.4	0.5	0.4	0.2
	Test 2	0.2	0.1	0.3	0.2	1.4
	Average	*0.2*	*0.2*	*0.4*	*0.3*	*0.7*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 0.6	0.7
2	± 0.5	0.9
Average	*± 0.5*	*0.8*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 1.8	7.3	N

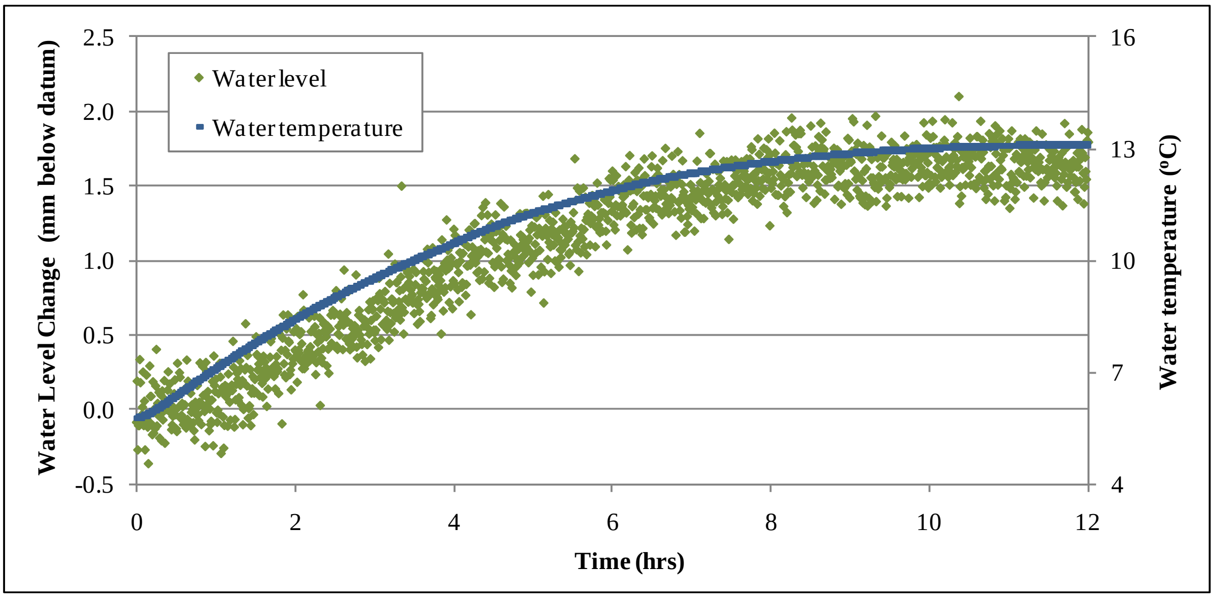

Figure 1 - Results of temperature compensation test

2. Field Results

Sensor appears to drift linearly until day 85 when the data became more erratic. This adversely affects the sensor accuracy. Sensor accuracy was ± 11 mm prior to day 85.

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 22	15

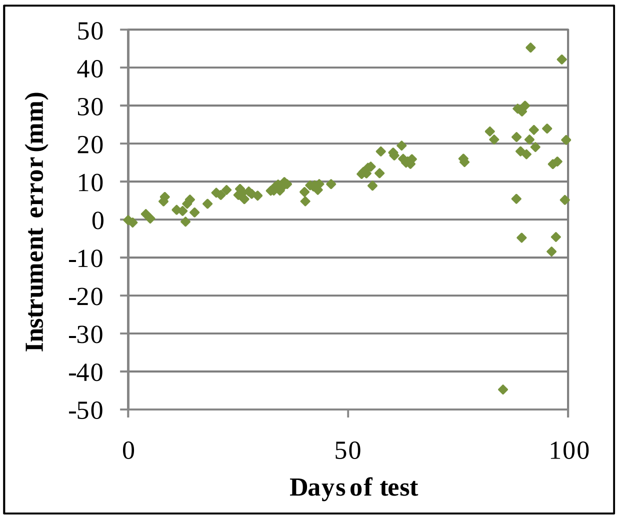

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Sensor 2

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	0.0	0.3	0.6	0.3	0.9
	Test 2	0.1	0.1	0.2	0.1	1.5
	Average	*0.0*	*0.2*	*0.4*	*0.1*	*1.2*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 0.6	0.7
2	± 0.6	0.9
Average	*± 0.6*	*0.8*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 1.4	7.1	N

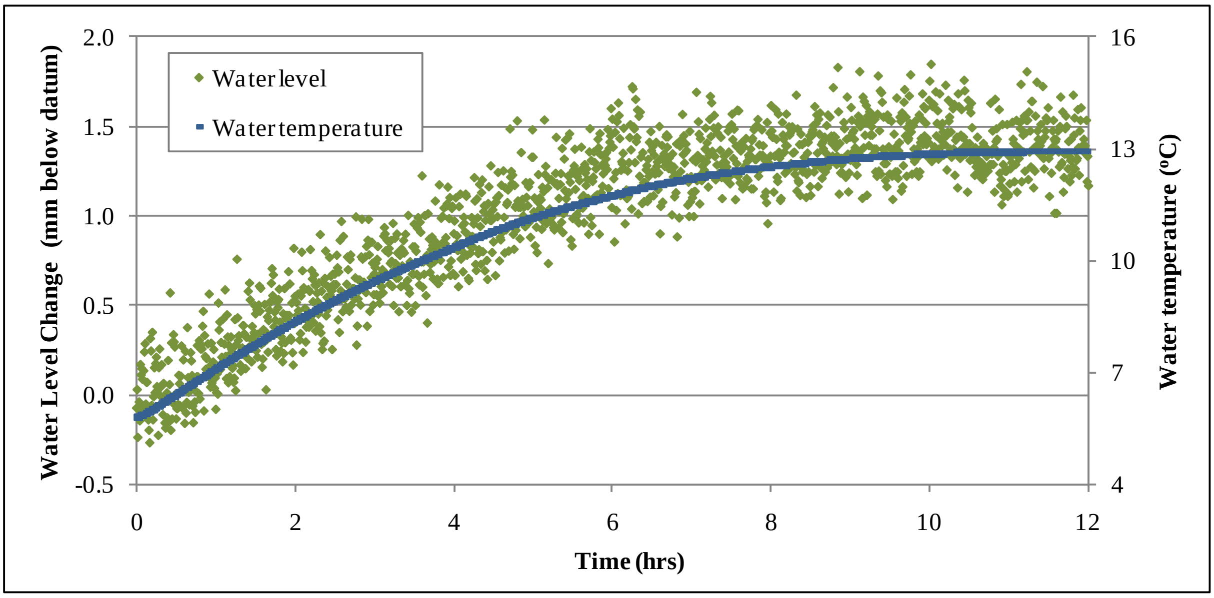

Figure 1 - Results of temperature compensation test

2. Field Results

Sensor appears to drift linearly throughout test period.

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 12	19

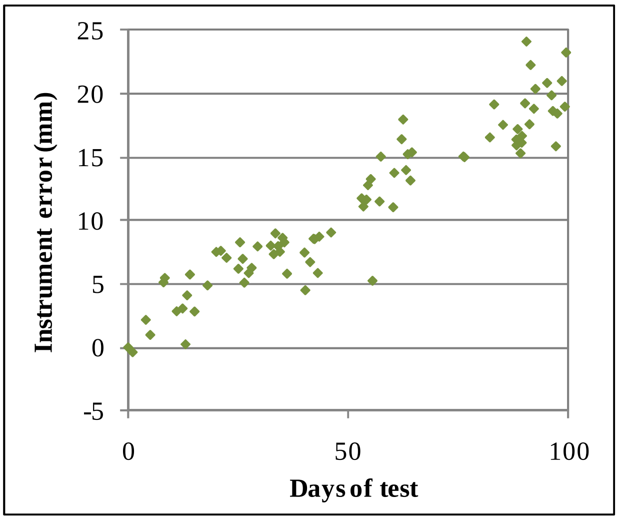

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Appendix C – Results of Transducer C

Sensor 1

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	0.2	0.6	0.6	0.1	2.6
	Test 2	0.2	0.6	0.4	0.0	1.2
	Average	*0.2*	*0.6*	*0.5*	*0.0*	*1.9*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	- *	- *
2	± 0.6	1.0
Average	*± 0.6*	*0.9*

** test affected by cable movement*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 0.5	7.0	N

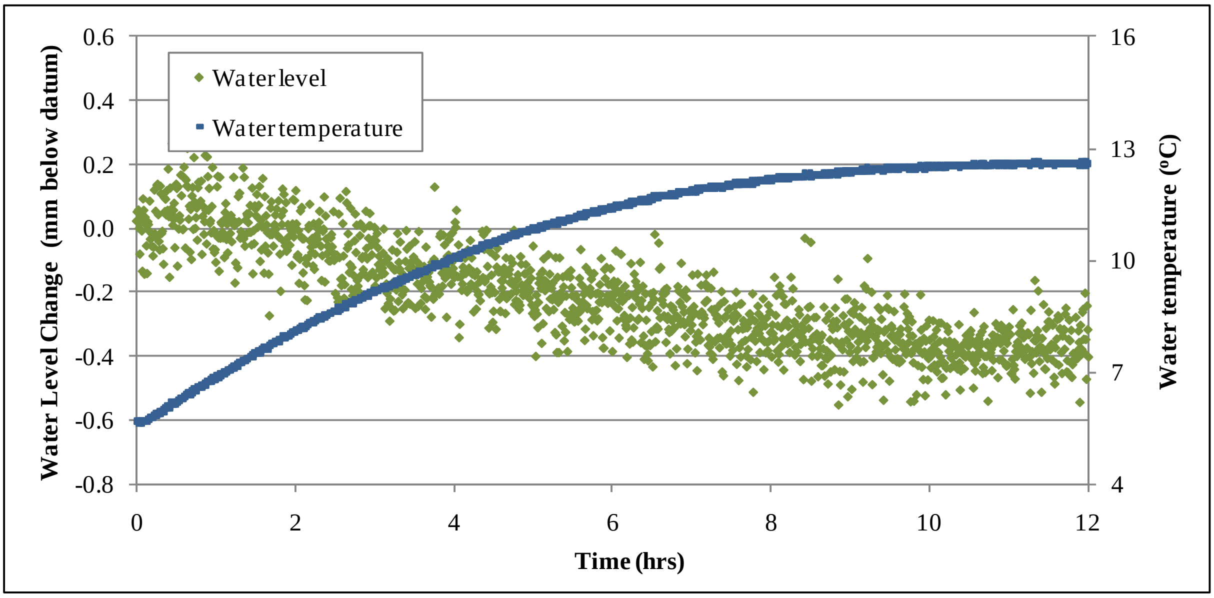

Figure 1 - Results of temperature compensation test

2. Field Results

Sensor appears to drift linearly throughout test period.

Table 4 – Field accuracy and drift results over 64 days

Accuracy (mm)	Drift (mm)
± 8	13

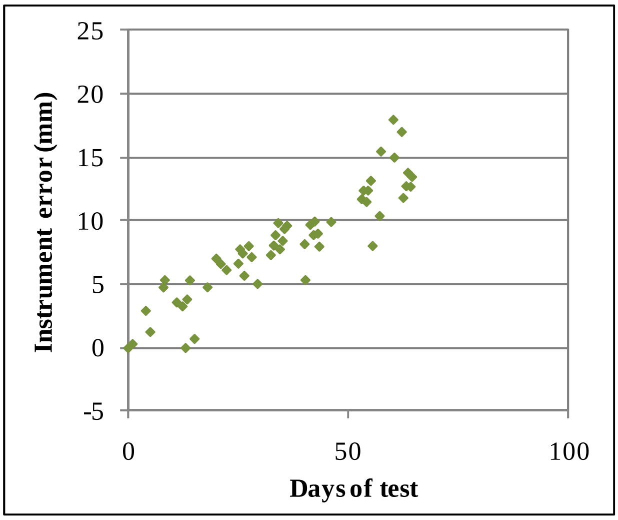

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Sensor 2

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	0.1	0.3	0.6	0.1	0.1
	Test 2	0.1	0.1	0.3	0.1	0.9
	Average	*0.1*	*0.1*	*0.4*	*0.1*	*0.5*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 0.3	0.8
2	± 0.4	1.0
Average	*± 0.4*	*0.9*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 0.5	6.7	N

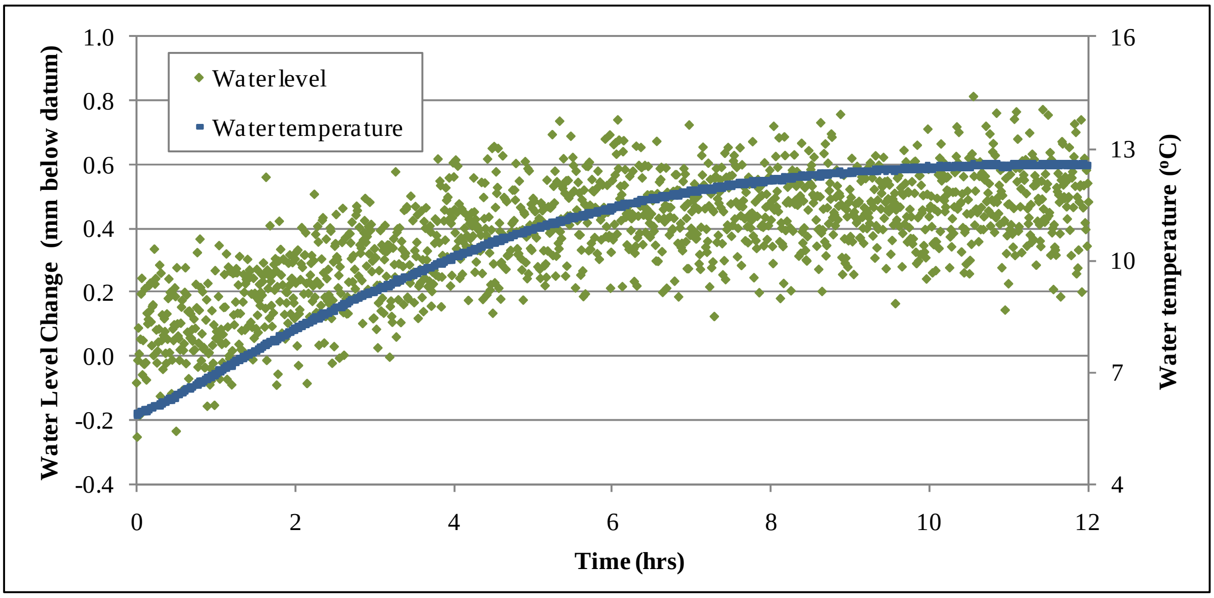

Figure 1 - Results of temperature compensation test

2. Field Results

Sensor appears to drift linearly throughout test period.

Table 4 – Field accuracy and drift results over 64 days

Accuracy (mm)	Drift (mm)
± 9	13

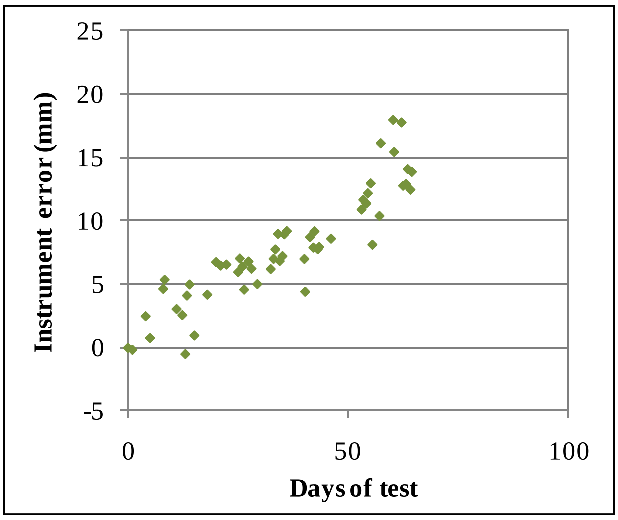

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Appendix D – Results of Transducer D

Sensor 1

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	0.1	0.0	0.9	0.0	3.0
	Test 2	0.2	0.7	0.0	1.0	4.0
	Average	*0.1*	*0.3*	*0.4*	*0.5*	*3.5*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 0.4	-
2	± 2.5	-
Average	± *1.5*	-

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 1.3	-	N

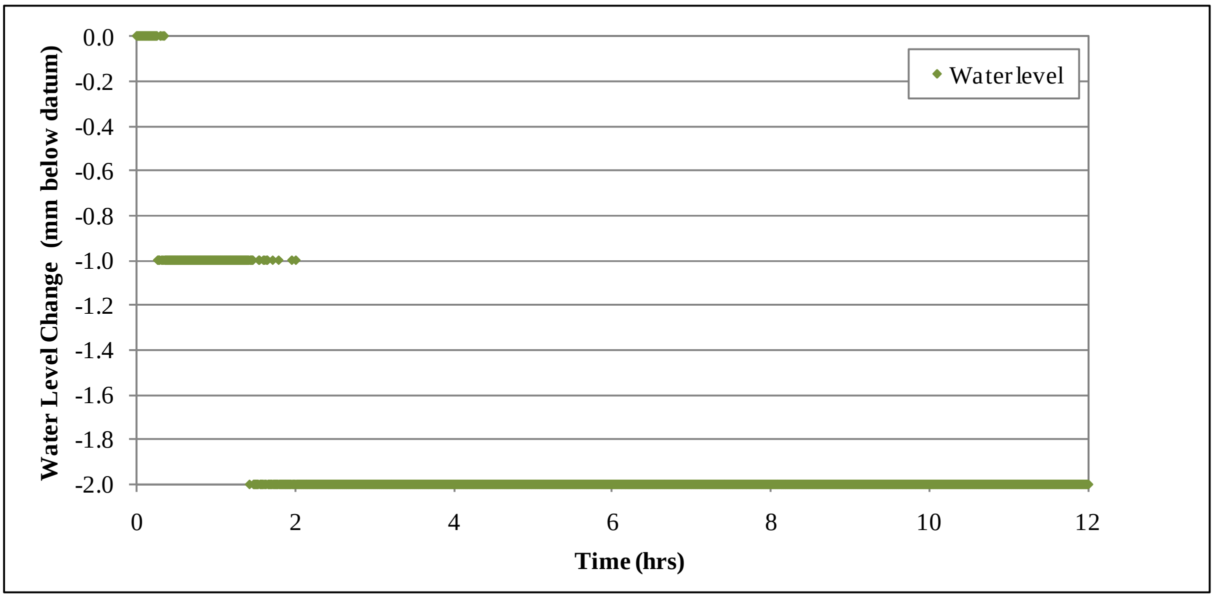

Figure 1 - Results of temperature compensation test

2. Field Results

Unit failed during test.

Sensor 2

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	0.0	0.0	1.0	0.0	0.9
	Test 2	0.0	0.0	0.0	1.0	3.0
	Average	*0.0*	*0.0*	*0.5*	*0.5*	*2.0*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 1.5	-
2	± 1.5	-
Average	*± 1.5*	-

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 0.7	-	N

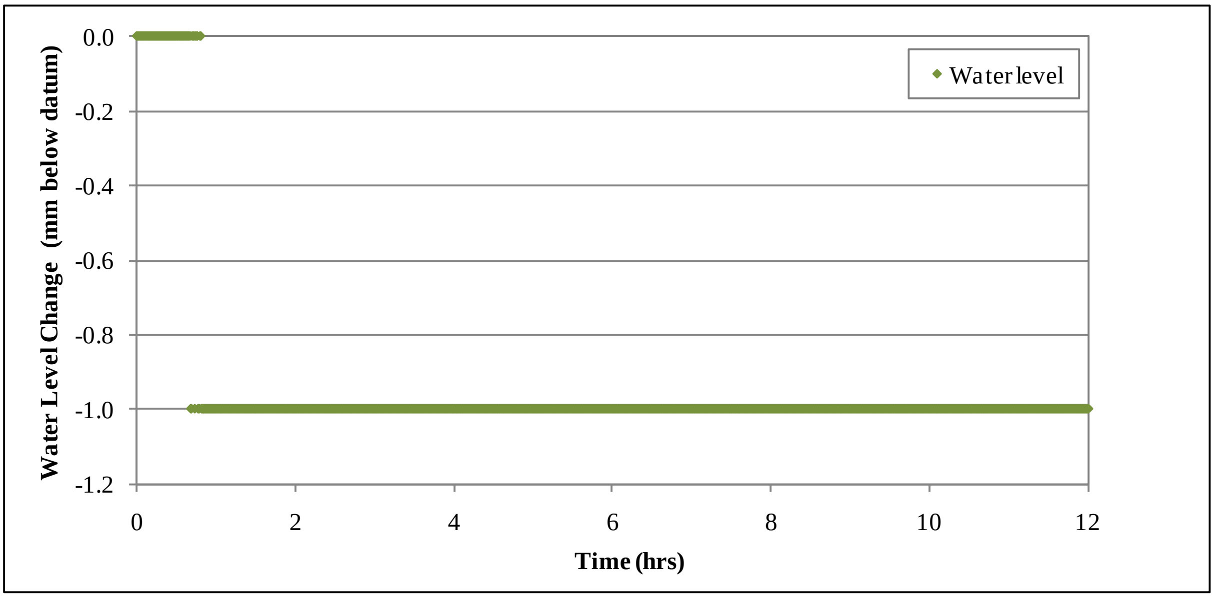

Figure 1 - Results of temperature compensation test

2. Field Results

Sensor appears to drift linearly throughout test period.

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 9	10

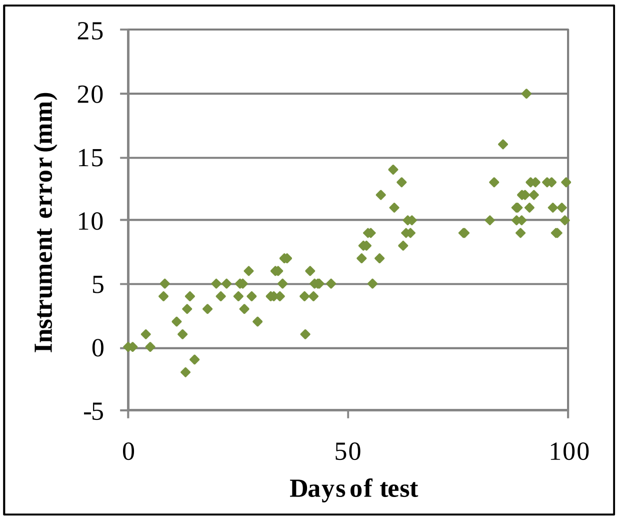

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Appendix E – Results of Transducer O

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	1.3	0.7	0.2	2.8	0.8
	Test 2	0.9	0.8	0.5	0.4	2.2
	Average	*1.1*	*0.7*	*0.3*	*1.6*	*1.5*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 4.7	0.6
2	± 4.4	0.6
Average	*± 4.5*	*0.6*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 5.8	2.6	Y

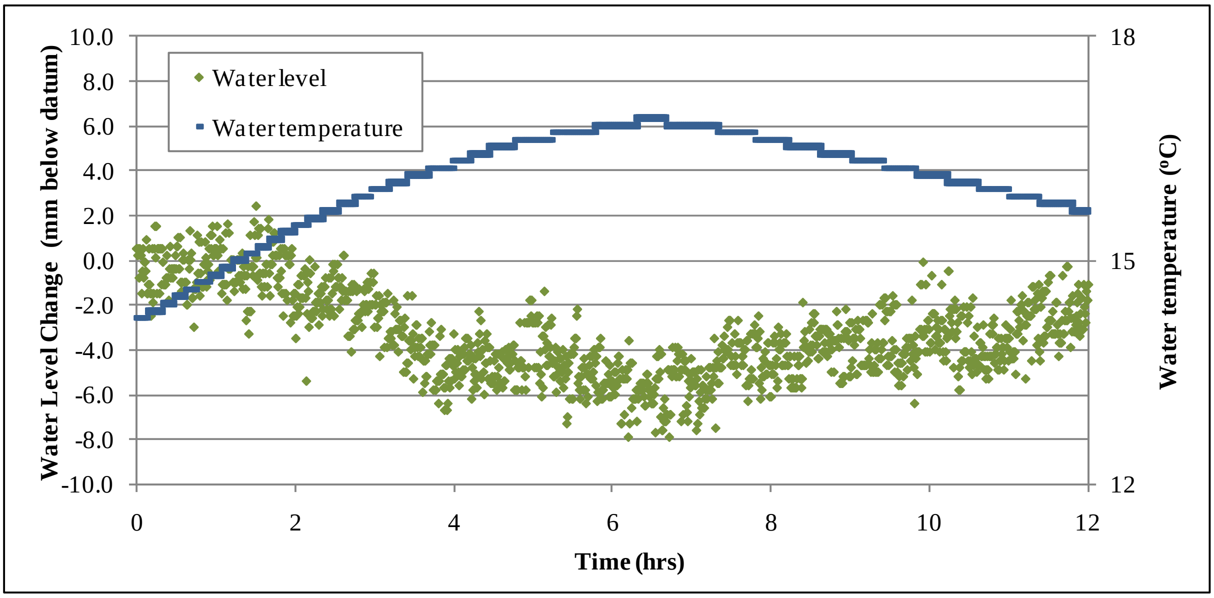

Figure 1 - Results of temperature compensation test

2. Field Results

This sensor was used to monitor atmospheric pressure for the compensation of Transducer G.

Appendix F – Results of Transducer G

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	0.7	1.0	0.8	0.6	2.4
	Test 2	1.2	0.4	0.3	0.3	0.6
	Average	*0.9*	*0.7*	*0.5*	*0.4*	*1.5*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 3.1	0.7
2	± 4.1	0.5
Average	*± 3.6*	*0.6*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 6.4	6.1	Y

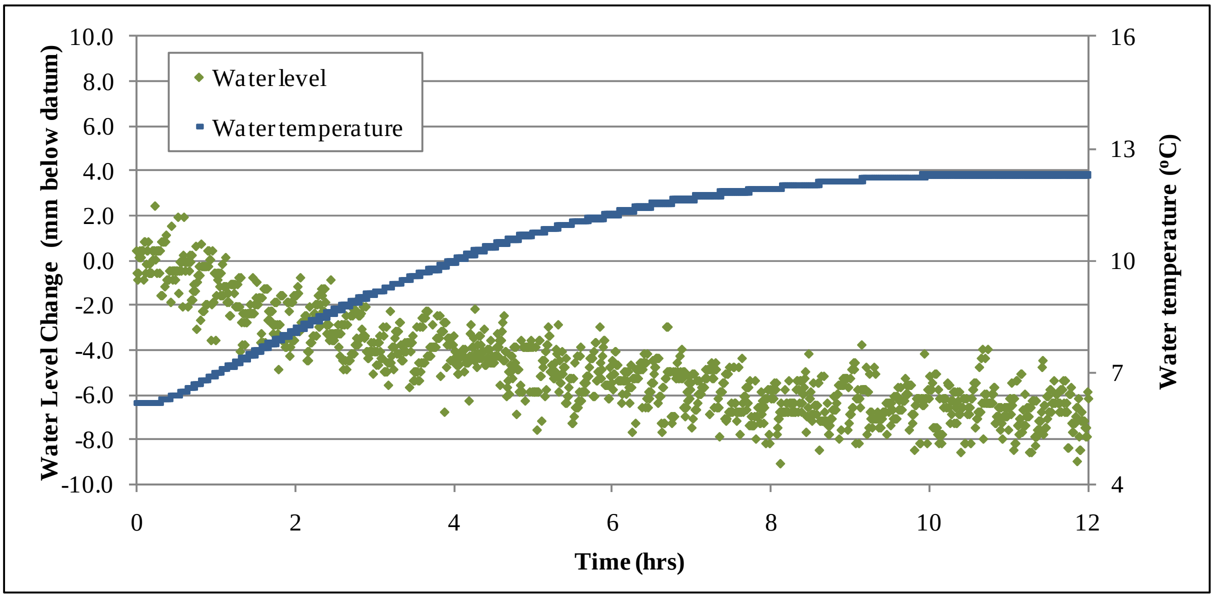

Figure 1 - Results of temperature compensation test

2. Field Results

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 7	-5

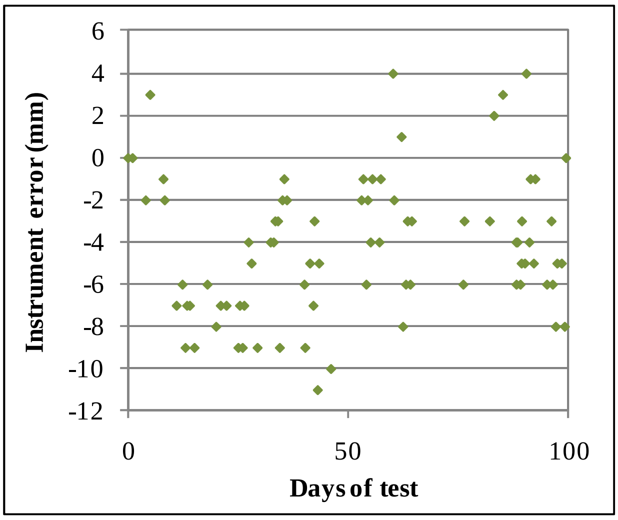

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Appendix G – Results of Transducer H

Sensor 1

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	0.0	0.2	0.5	0.2	2.0
	Test 2	0.2	0.2	0.3	0.3	2.6
	Average	*0.1*	*0.2*	*0.4*	*0.2*	*2.3*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 1.2	0.7
2	± 1.2	0.9
Average	*± 1.2*	*0.8*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 1.3	6.9	N

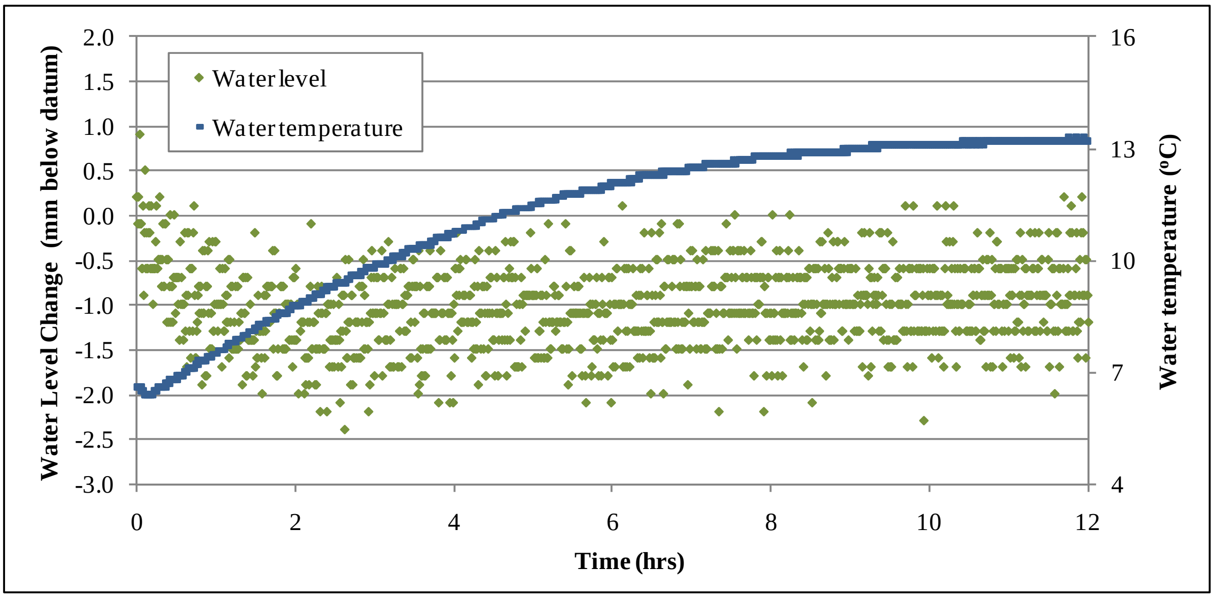

Figure 1 - Results of temperature compensation test

2. Field Results

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 5	-1

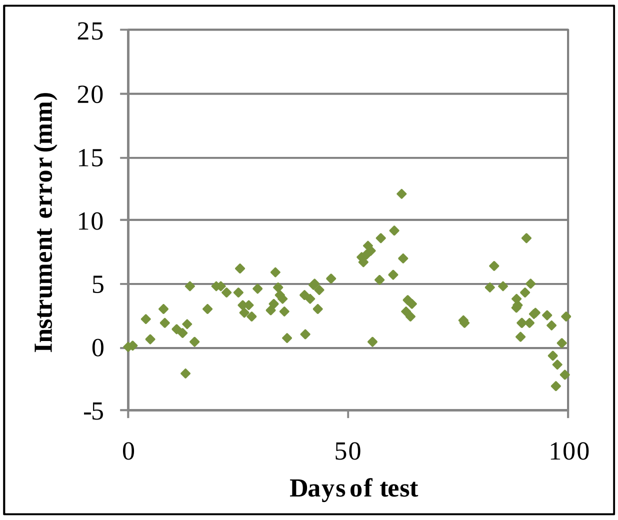

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Sensor 2

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	0.1	0.3	0.6	0.1	1.3
	Test 2	0.3	0.3	0.2	0.3	2.3
	Average	*0.2*	*0.3*	*0.4*	*0.2*	*1.8*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 1.2	0.7
2	± 1.1	0.9
Average	*± 1.2*	*0.8*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 1.8	6.7	N

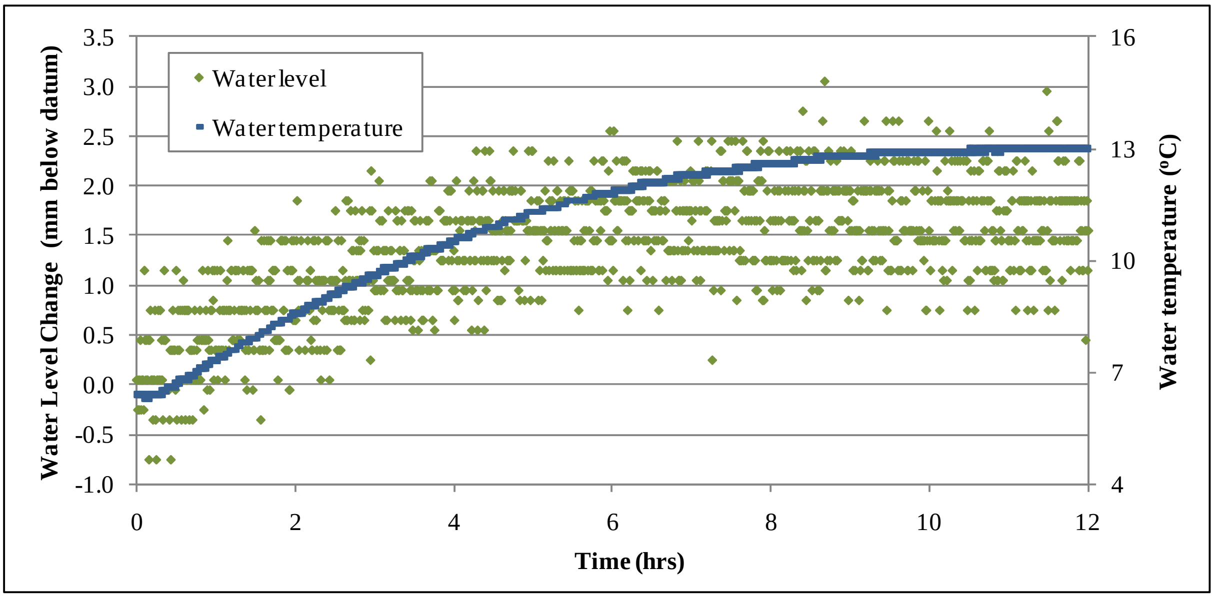

Figure 1 - Results of temperature compensation test

2. Field Results

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 5	-2

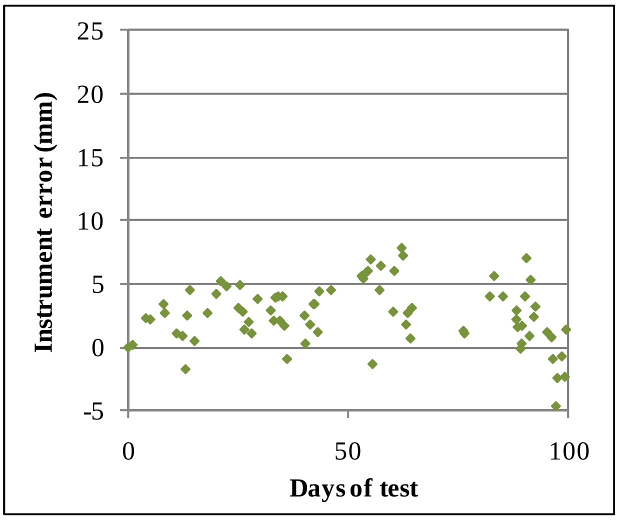

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Appendix H – Results of Transducer I

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	3.5	3.6	1.9	15.4	7.6
	Test 2	1.2	0.9	0.5	0.8	8.0
	Average	*2.3*	*2.2*	*1.2*	*8.1*	*7.8*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 14.7	0.6
2	± 16.9	0.7
Average	± *15.8*	*0.7*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 44.8	6.3	Y

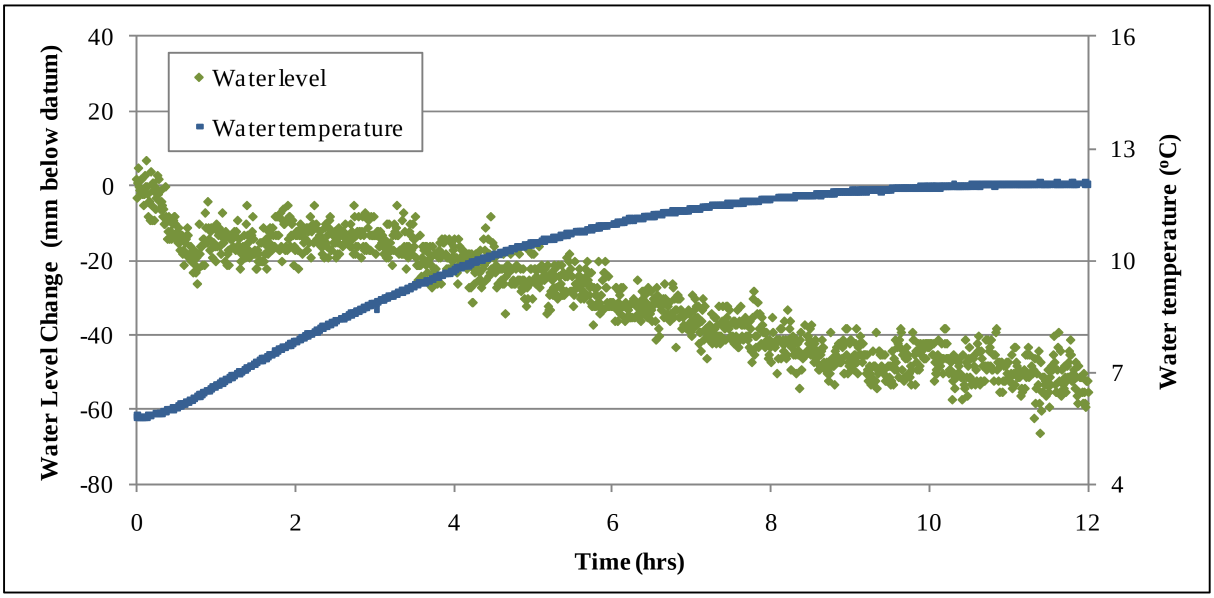

Figure 1 - Results of temperature compensation test

2. Field Results

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 46	73

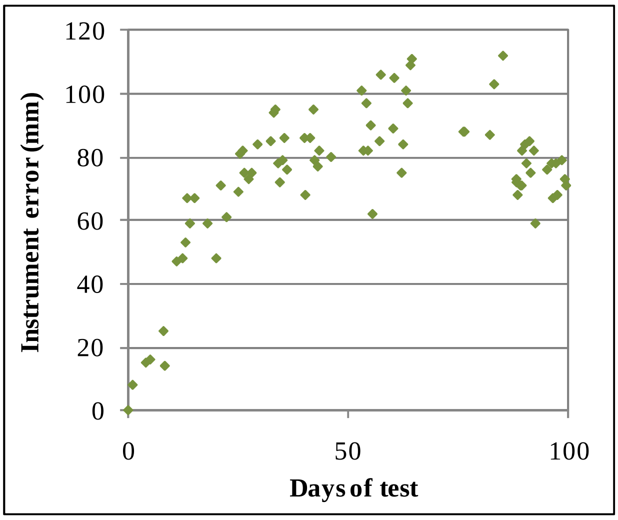

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Appendix I – Results of Transducer J

Sensor 1

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	1.3	0.4	2.8	0.2	4.5
	Test 2	1.3	1.7	0.7	1.2	5.5
	Average	*1.3*	*1.0*	*1.7*	*0.7*	*5.0*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 7.1	0.7
2	± 7.6	1.5
Average	*± 7.3*	*1.1*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 10.4	7.3	Y

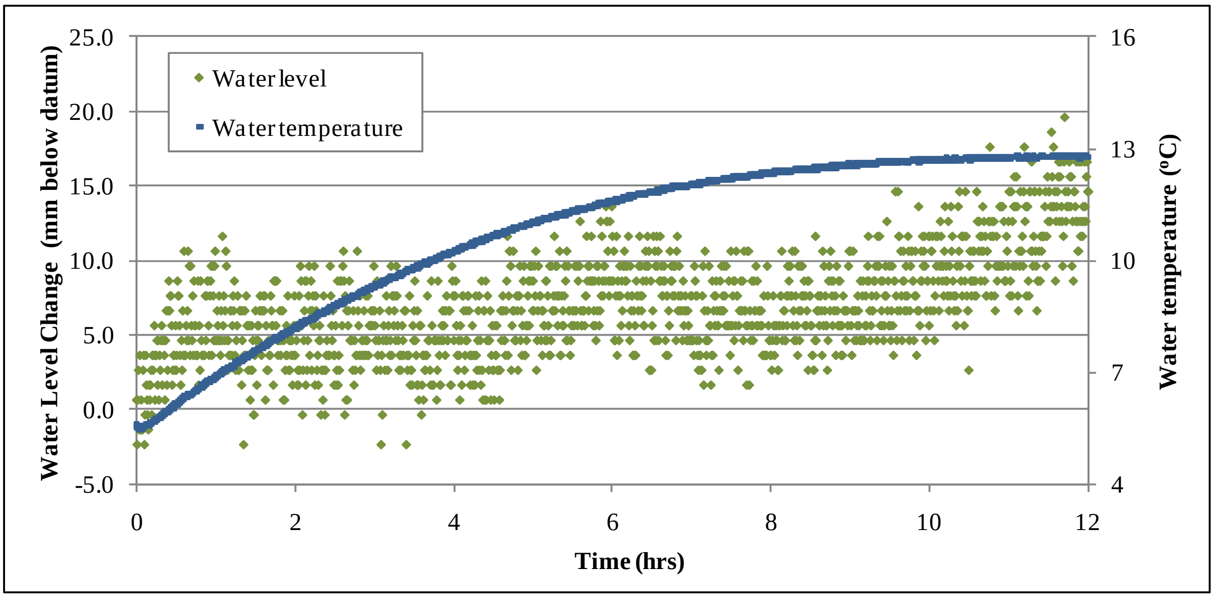

Figure 1 - Results of temperature compensation test

2. Field Results

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 13	-8

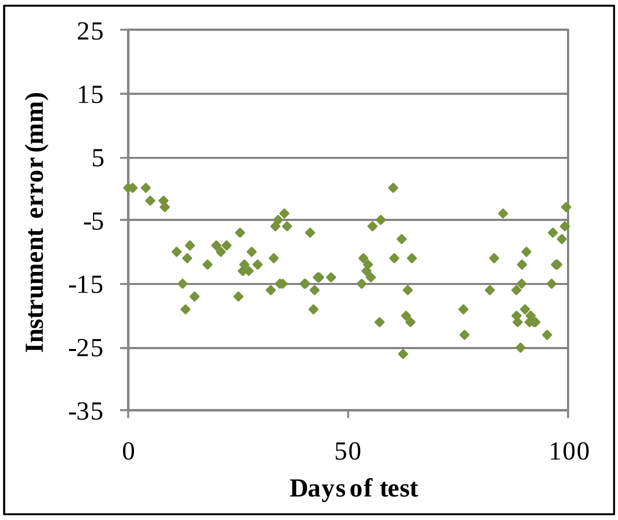

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Sensor 2

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	0.1	0.7	0.3	1.4	3.5
	Test 2	1.6	0.2	0.1	0.2	6.9
	Average	*0.8*	*0.4*	*0.2*	*0.8*	*5.2*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 6.2	0.8
2	± 6.7	1.8
Average	± *6.4*	*1.3*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 11.3	6.1	Y

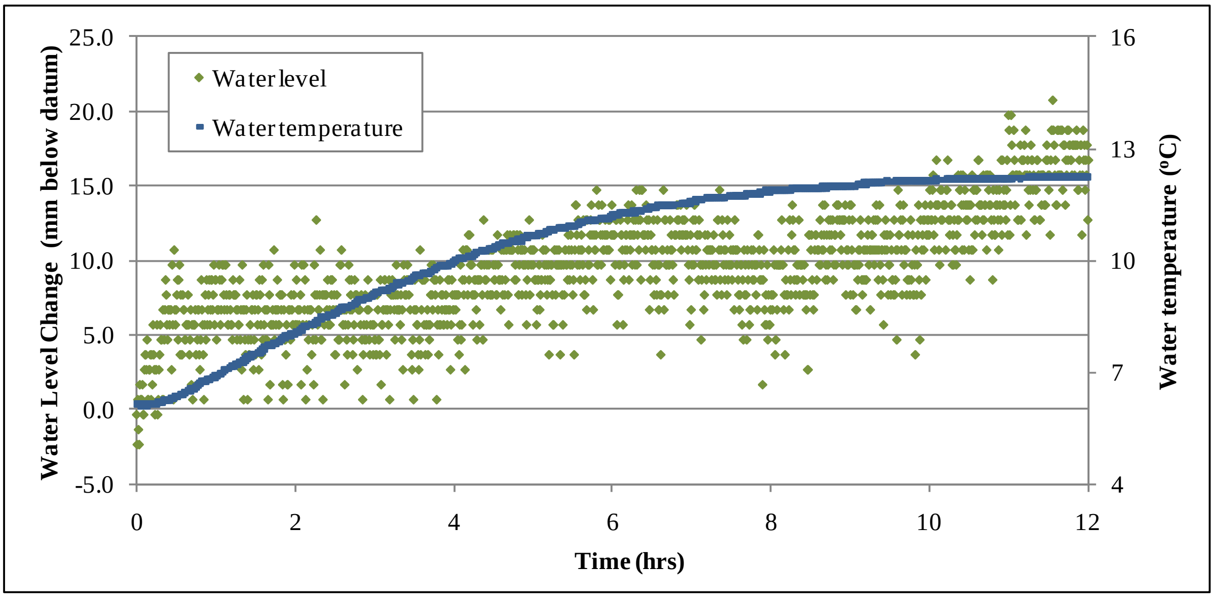

Figure 1 - Results of temperature compensation test

2. Field Results

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 11	-7

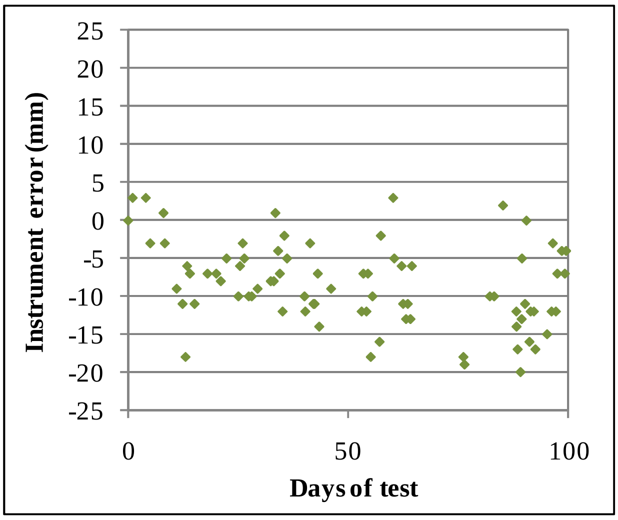

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Appendix J – Results of Transducer K

Sensor 1

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	14.1	1.0	10.0	30.4	25.8
	Test 2	11.4	1.0	1.4	13.2	25.4
	Average	*12.7*	*1.0*	*5.7*	*21.8*	*25.6*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 42.2	0.6
2	± 35.8	0.6
Average	*± 39.0*	*0.6*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 97.6	6.5	Y

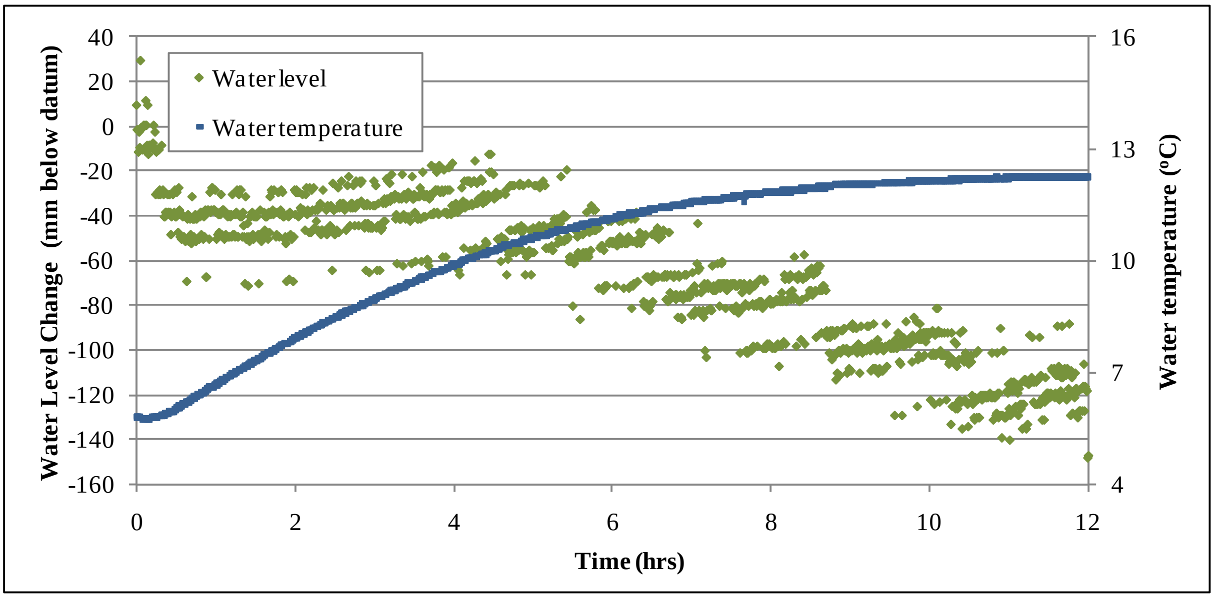

Figure 1 - Results of temperature compensation test

2. Field Results

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 65	95

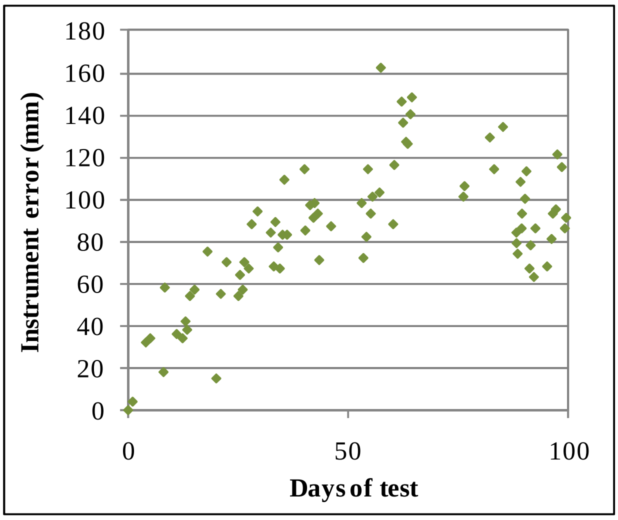

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Sensor 2

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	13.2	9.3	16.1	57.1	18.0
	Test 2	2.1	4.2	3.8	5.9	23.7
	Average	*7.6*	*6.7*	*10.0*	*31.5*	*20.8*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 33.1	0.7
2	± 42.2	0.7
Average	*± 37.6*	*0.7*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 136.7	6.5	Y

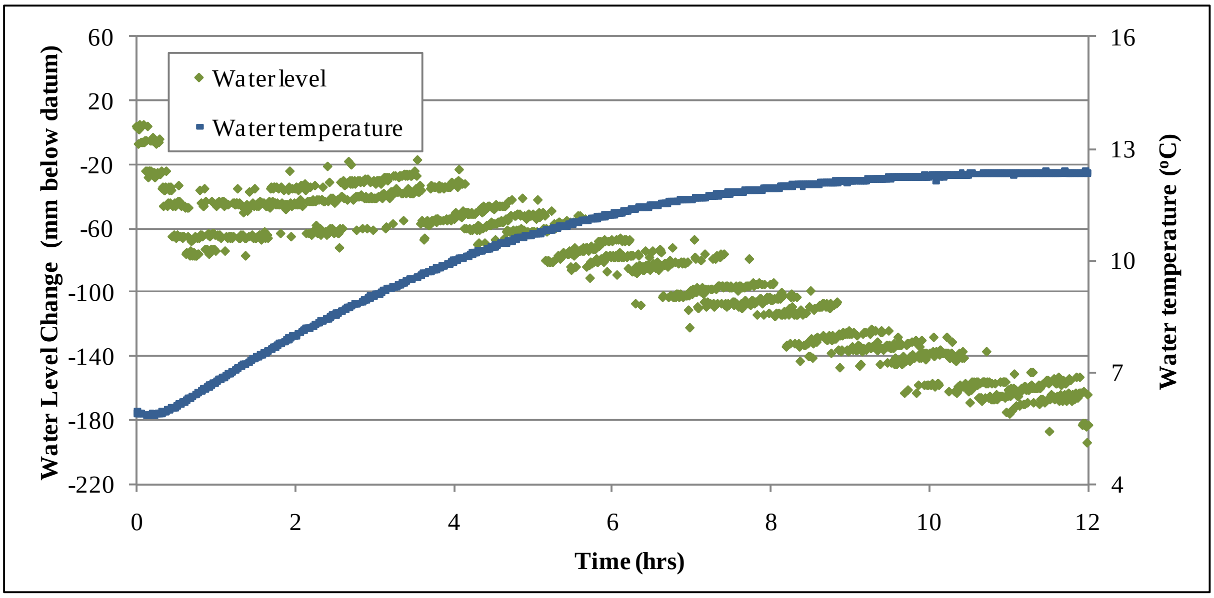

Figure 1 - Results of temperature compensation test

2. Field Results

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 85	181

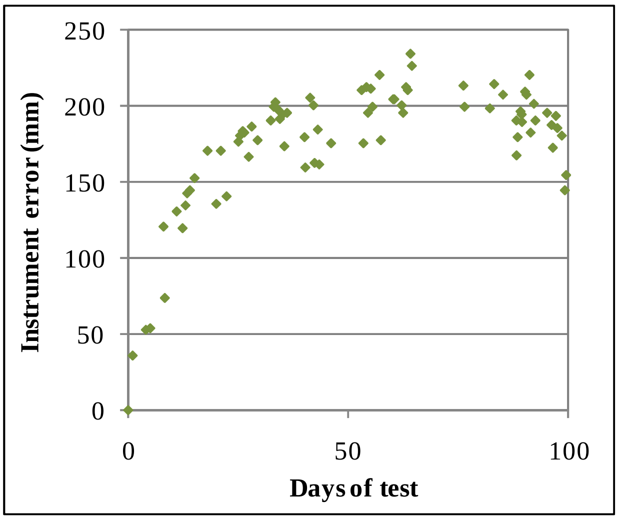

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Appendix K – Results of Transducer L

Sensor 1

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	1.1	0.1	0.2	36.6	8.7
	Test 2	3.2	1.3	16.5	3.4	6.0
	Average	*2.1*	*0.7*	*8.3*	*20.0*	*7.3*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 42.3	0.7
2	± 106.1	0.7
Average	± *74.2*	*0.7*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 90.8	6.7	Y

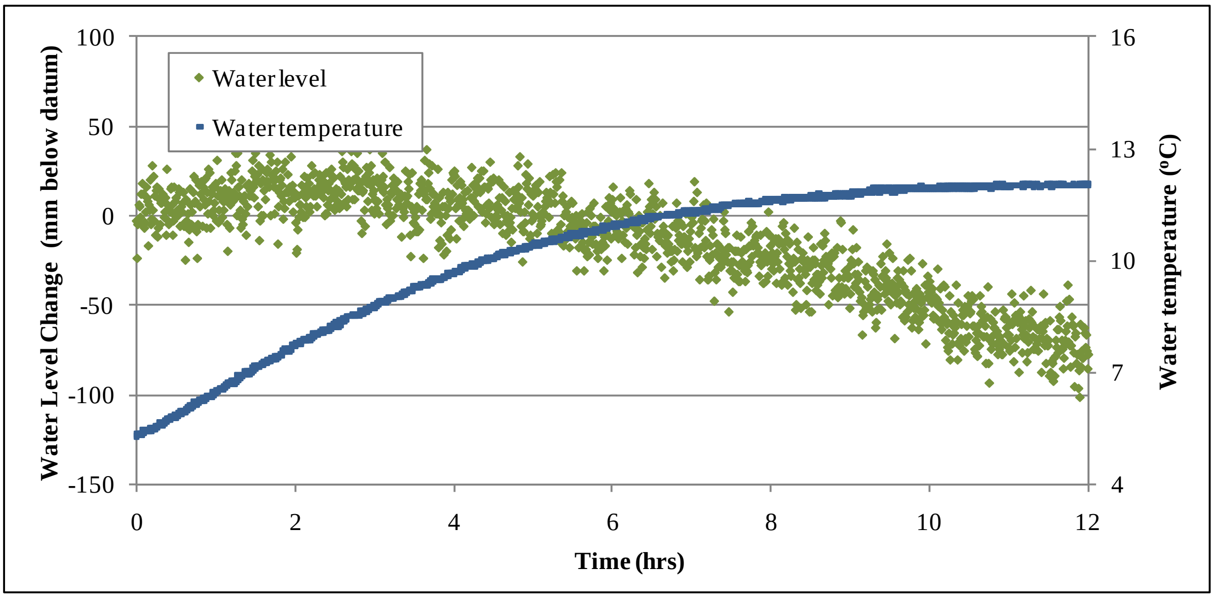

Figure 1 - Results of temperature compensation test

2. Field Results

Unit failed during test.

Sensor 2

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	0.9	0.1	2.5	0.5	1.0
	Test 2	0.6	0.0	1.3	0.2	5.8
	Average	*0.7*	*0.0*	*1.9*	*0.3*	*3.4*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 7.8	0.6
2	± 7.5	0.5
Average	*± 7.6*	*0.6*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 7.1	6.5	N

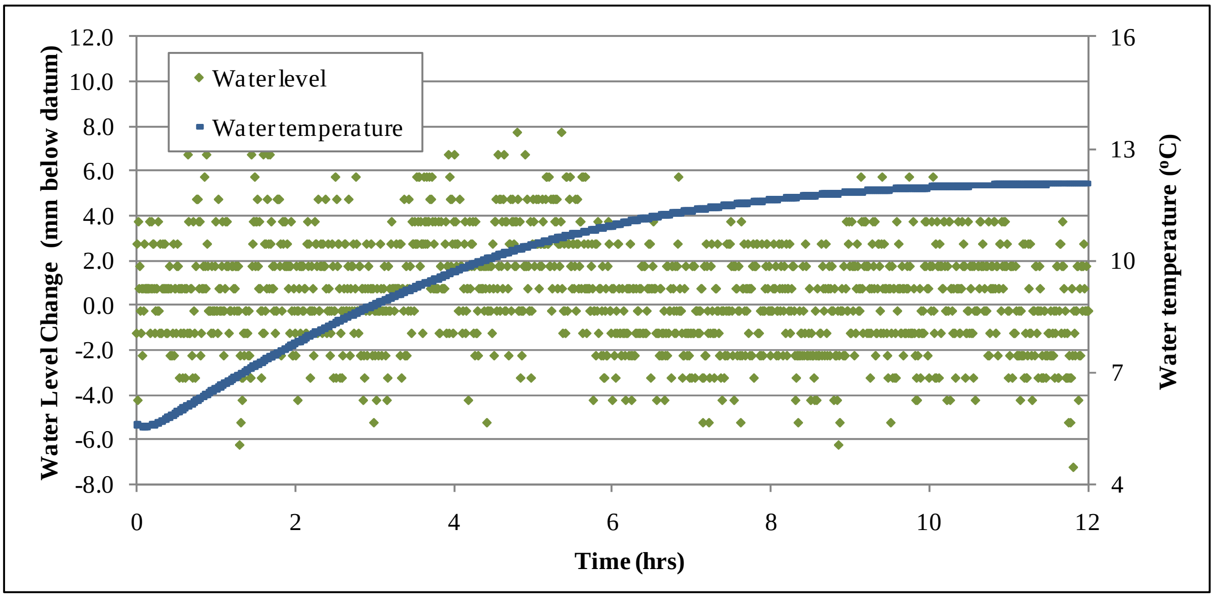

Figure 1 - Results of temperature compensation test

2. Field Results

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 8	6

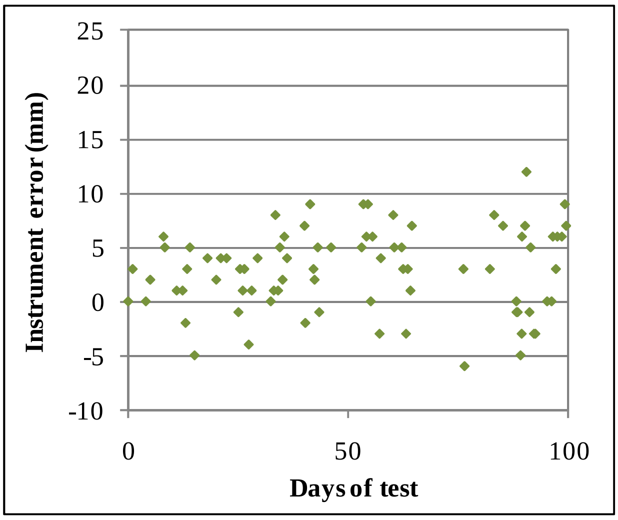

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Appendix L – Results of Transducer M

Sensor 1

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	0.3	1.9	0.7	1.2	0.9
	Test 2	0.7	0.5	0.6	0.6	3.0
	Average	*0.5*	*1.2*	*0.6*	*0.9*	*2.0*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 5.9	0.6
2	± 6.4	0.6
Average	*± 6.1*	*0.6*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 5.9	6.6	N

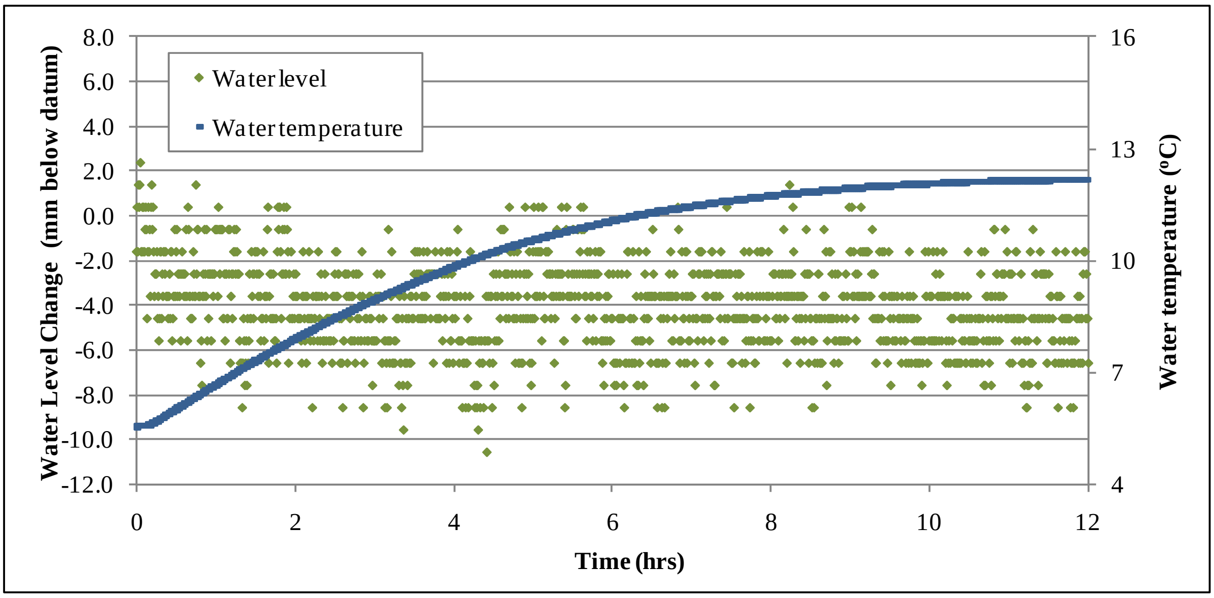

Figure 1 - Results of temperature compensation test

2. Field Results

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 8	9

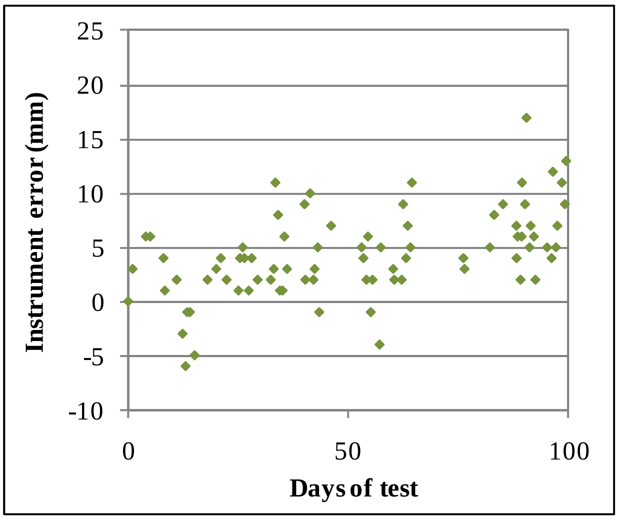

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Sensor 2

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	1.0	0.3	0.7	1.4	2.2
	Test 2	1.7	0.5	0.5	0.1	3.9
	Average	*1.3*	*0.4*	*0.6*	*0.7*	*3.0*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 6.2	0.6
2	± 6.6	0.5
Average	*± 6.4*	*0.6*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 5.9	6.1	N

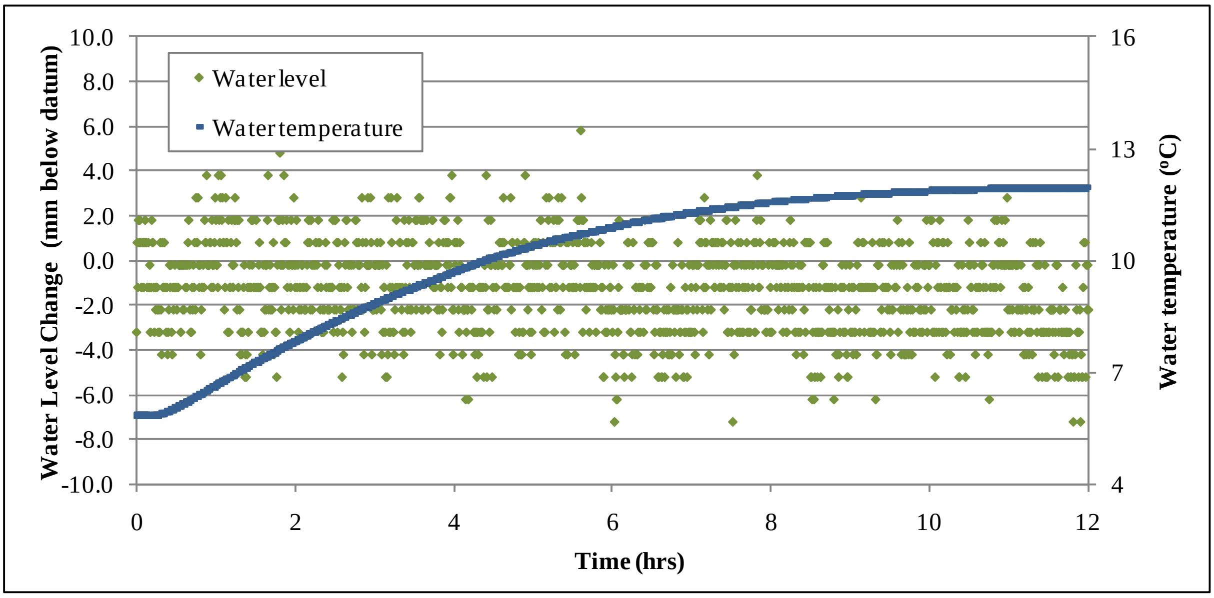

Figure 1 - Results of temperature compensation test

2. Field Results

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 8	9

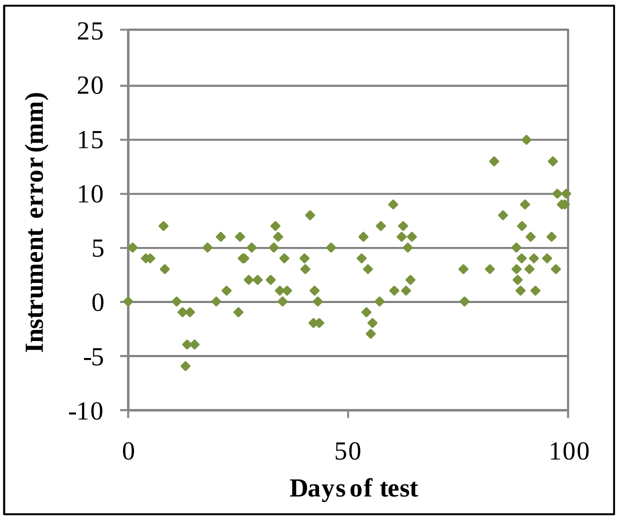

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Appendix M – Results of Transducer N

Sensor 1

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	0.0	0.2	0.8	0.3	2.8
	Test 2	0.6	0.8	0.3	0.3	3.4
	Average	*0.3*	*0.5*	*0.5*	*0.3*	*3.1*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 0.8	0.6
2	± 0.8	0.5
Average	*± 0.8*	*0.6*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 5.1	5.9	Y

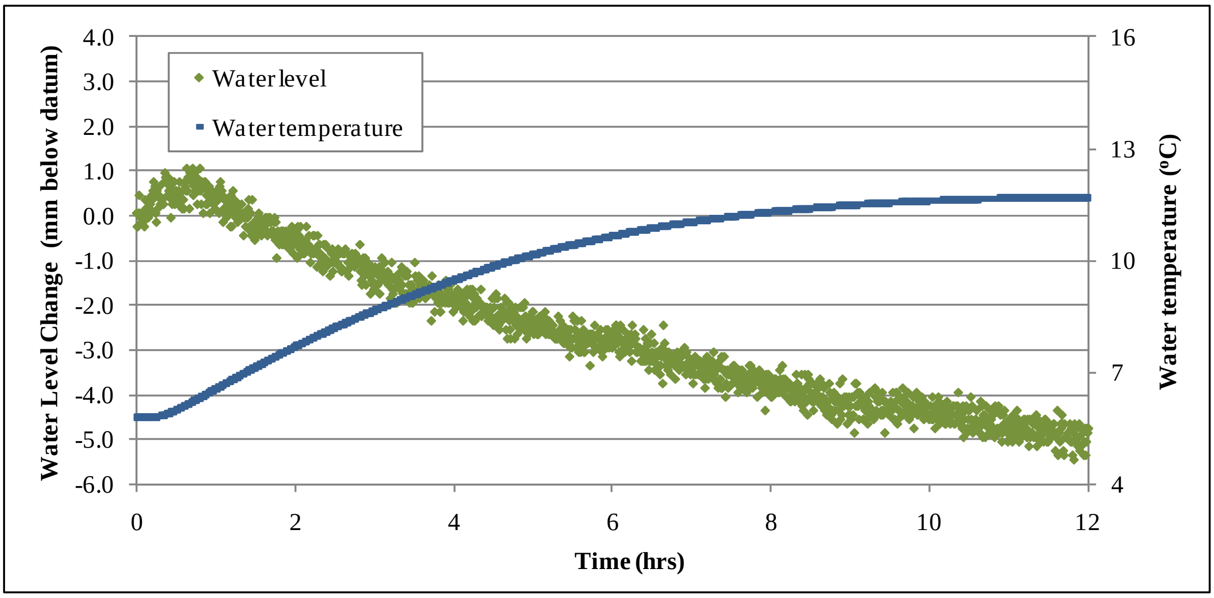

Figure 1 - Results of temperature compensation test

2. Field Results

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 11	17

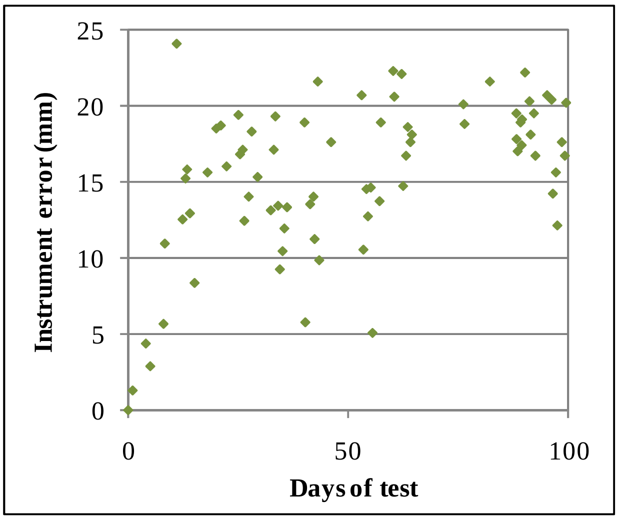

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Sensor 2

1. Laboratory Results

1.1 Accuracy

Table 1 - Laboratory accuracy results

Water level change (mm)		10	20	50	200	1000
Error (mm)	Test 1	0.1	0.3	0.7	0.6	1.4
	Test 2	0.4	0.8	0.2	0.3	2.4
	Average	*0.2*	*0.5*	*0.4*	*0.4*	*1.9*

1.2 Precision

Table 2 – Laboratory precision results

Test	Water level variation (mm)	Water temperature change (°C)
1	± 0.8	0.6
2	± 0.6	0.5
Average	*± 0.7*	*0.6*

1.3 Temperature compensation

Table 3 – Laboratory temperature compensation results

Water level variation (mm)	Water temperature variation (°C)	Significant?
± 7.1	5.7	Y

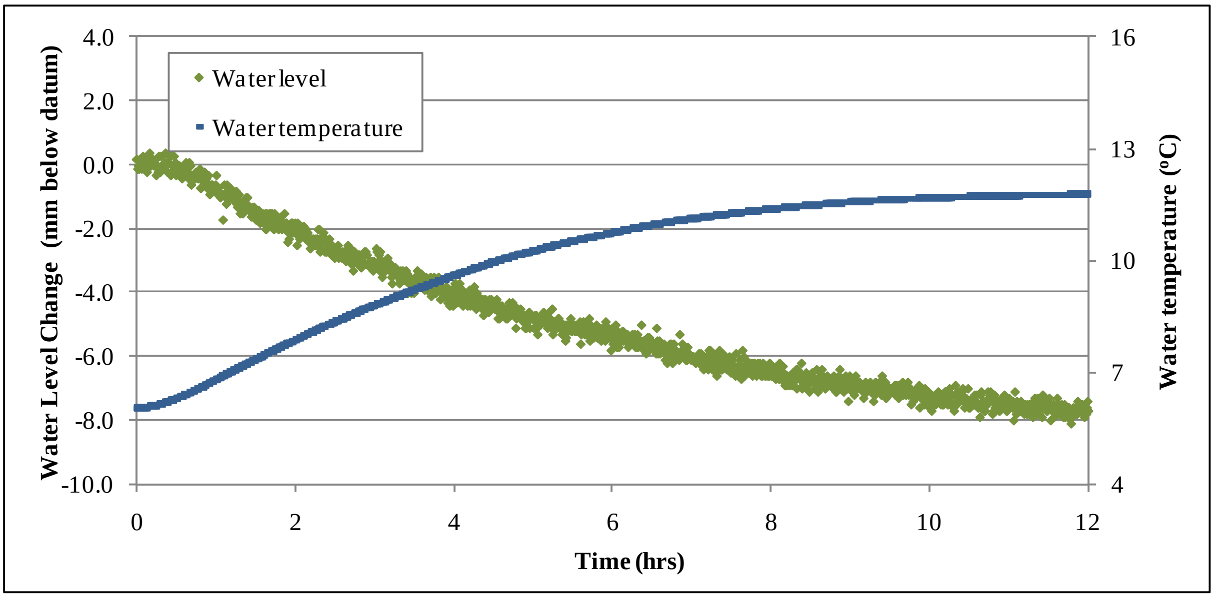

Figure 1 - Results of temperature compensation test

2. Field Results

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 10	12

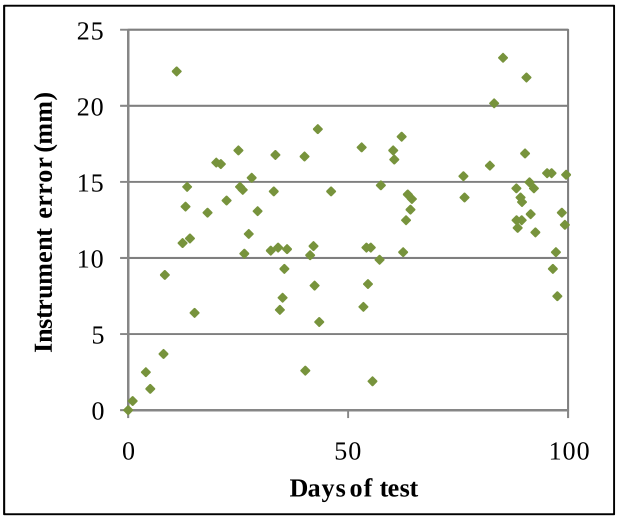

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Appendix N – Results of Transducer E

Sensor 1

1. Field Results

Table 1 – Field accuracy and drift results over 89 days

Accuracy (mm)	Drift (mm)
± 27	27

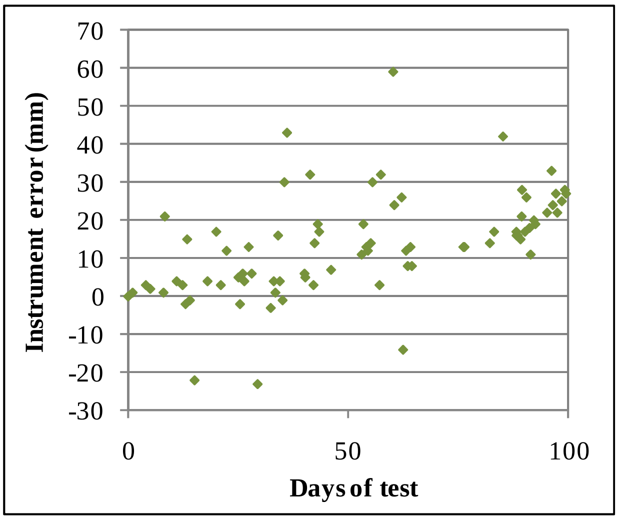

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Sensor 2

1. Field Results

Table 1 – Field accuracy and drift results over 64 days

Accuracy (mm)	Drift (mm)
± 28	27

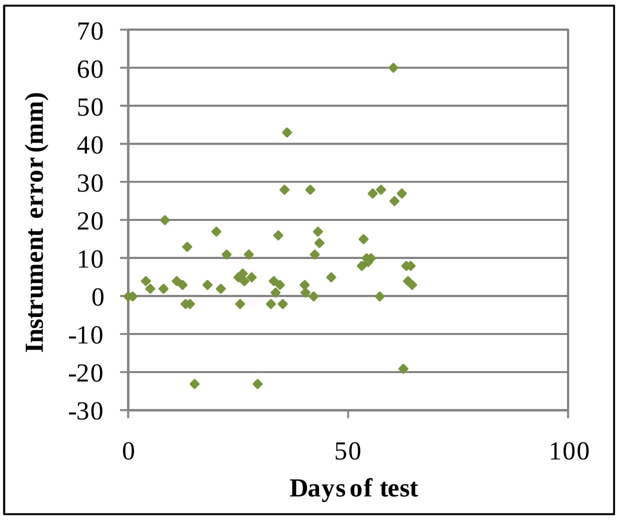

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Appendix O – Results of Transducer F

<u>Sensor 1</u>

1. Field Results

Table 4 – Field accuracy and drift results over 89 days

Accuracy (mm)	Drift (mm)
± 4	6

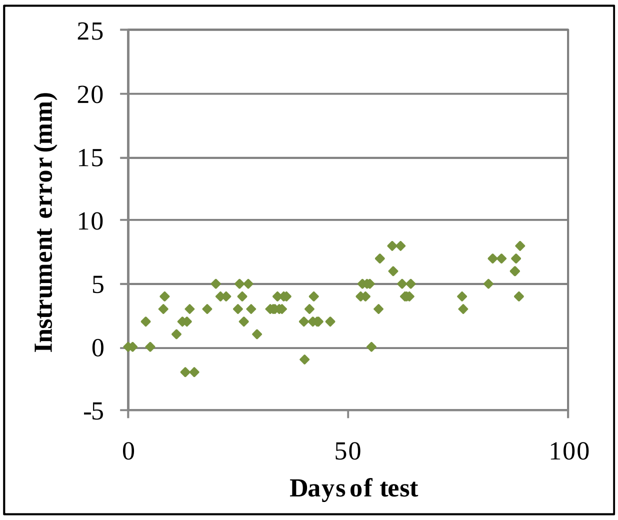

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Sensor 2

1. Field Results

Table 1 – Field accuracy and drift results over 89 days

Accuracy (mm)	Drift (mm)
± 4	5

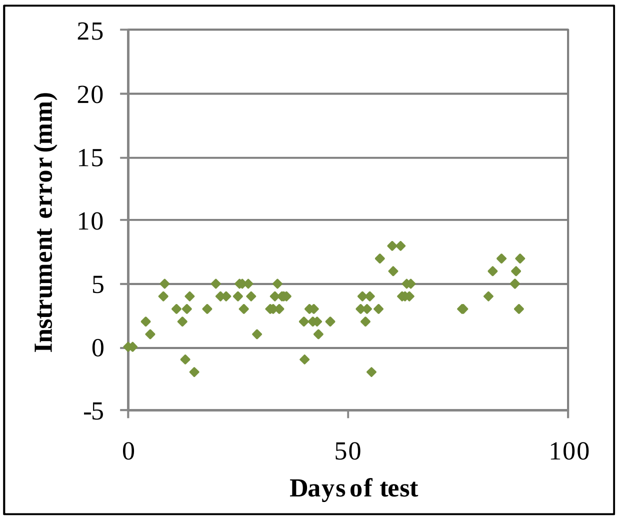

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Appendix P – Results of capacitance water level probe

Sensor 1

2. Field Results

Table 4 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 117	-

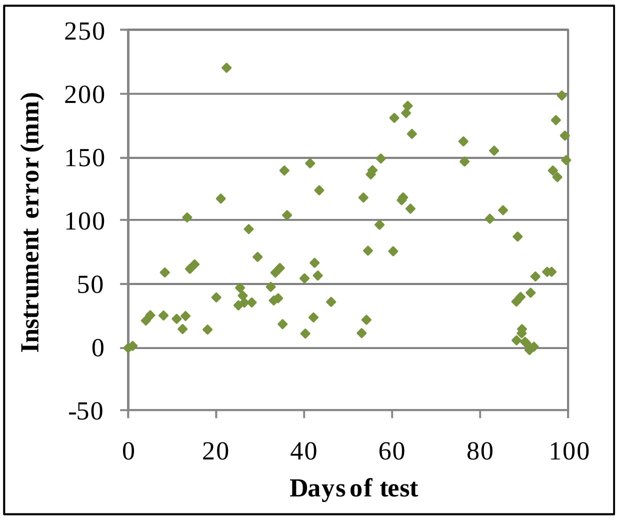

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading

Sensor 2

2. Field Results

Table 1 – Field accuracy and drift results over 99 days

Accuracy (mm)	Drift (mm)
± 160	-

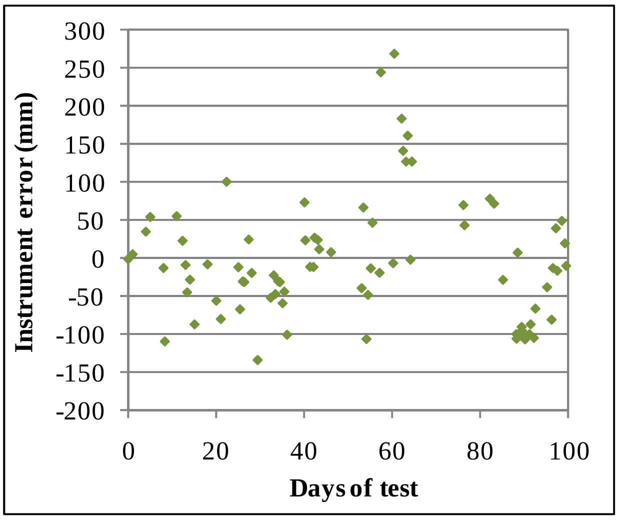

Figure 2 - Field test results – instrument error is dip measurement minus transducer reading