DO PIEZOMETER AND STANDPIPE MATERIALS INFLUENCE THE MEASUREMENT OF SHALLOW GROUNDWATER TEMPERATURES?

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ABSTRACT
Accurate measurements of *in situ* groundwater temperature are important in many groundwater investigations. Temperature is often measured in the subsurface using an access tube in the form of a piezometer or monitoring well. The impact of standpipe materials on the conduction of heat into the subsurface has not previously been examined. This paper reports on the results of a laboratory experiment and a field experiment designed to determine if different standpipe materials or monitoring instrument configurations preferentially conduct heat into the shallow subsurface. Statistical analysis of the laboratory results demonstrates that common standpipe materials, such as steel and polyvinylchloride (PVC), do not affect temperature in the subsurface. Field results show that different instrument configurations, such as piezometers and water and air filled and sealed well points, do not affect subsurface temperature measurements.

RÉSUMÉ
Avoir des mesures de température d'eau souterraine précise en situation est important dans plusieurs investigations d'eau sousterraine. La température est souvent mesurée dans la sous-surface avec l'aide d'un tube d'accès en forme de piézomètre ou d'un puis de surveillance. L'impact des matériaux de la colonne sur la conduction de la chaleur dans la sous-surface n'a pas été précédemment examiné. Cet article rapporte les résultas d'une expérience de laboratoire et d'une expérience sur le terrain conçu pour déterminer si l'utilisation de colonne de différent matériaux ou de différente configuration d'instrument de surveillance conduise préférentiellement la chaleur dans la sous-surface peu profonde. L'analyse statistique des résultas de laboratoire démontre que des matériaux de colonne commun, comme l'acier et le chlorure polyvinylique (PVC), n'affect pas la température dans la sous-surface. Les résultas sur le terrain montre que différente configuration d'instrument, comme des piézomètres et remplis d'eau et d'air et des points de puis sellés, n'affect pas les mesures de température de sous-surface.

1. INTRODUCTION

Accurate monitoring of *in situ* groundwater temperature is important in studies of groundwater recharge (Suzuki 1960; Stallman 1965), groundwater travel time determination (Bredehoeft and Papadopulos 1965), groundwater-surface water interaction studies focusing on groundwater-stream connectivity (Doussan et al. 1994), cold water fish habitat (Alexander and Caissie 2003), wetland hydrology (Hunt et al. 1996), and groundwater-marine water interaction (Land and Paull 2001). In such studies, small diameter piezometers and well points are often the instruments of choice in providing access for measuring groundwater temperature.

Two processes, convection and conduction, are responsible for the transfer of heat in groundwater systems (Bredehoeft and Papadopulos 1965). Free convection occurs when groundwater flow occurs solely due to density variations caused by temperature gradients. Forced convection occurs when groundwater flow is initiated and maintained by an external force. Heat conduction is important when the fluid flux is extremely low or nonexistent.

A series of papers (e.g., Hales 1936; Krige 1939; Donaldson 1961; Gretener 1967) has addressed the occurrence of free convection in boreholes and groundwater monitoring wells. These studies suggest that free convection, due to thermal instability, in small diameter wells (e.g., < 4 cm) is negligible in the shallow subsurface.

Although there has been research conducted on the topic of free convection in boreholes and standpipes there appears to be no previous investigations of thermal conduction in standpipe materials. Groundwater monitoring instruments (i.e., piezometers and well points) commonly extend some distance above the ground surface. Generally these instruments are constructed of materials such as steel or PVC that have the potential to transfer heat via conduction from the surface into or out of the ground. In shallow groundwater studies the piezometer or standpipe material volume (e.g., 3.44 cm outside diameter (OD) schedule 40 pipe) is almost equal to the volume of water contained inside. The thermal conductivity of the standpipe material is typically several times larger than the surrounding geological materials and groundwater (e.g., the thermal conductivity of steel is about two orders of magnitude greater than water). In this paper we report on laboratory and field investigations of shallow (i.e., < 1 m) groundwater temperature measurement in commonly used standpipe materials and instrument configurations.

2. METHODOLOGY

2.1 Laboratory Experiment

A 0.255 m^3 insulated plywood box was filled with an homogenous medium grained silica sand with a mean grain size diameter of 1.48 mm and a mean porosity of approximately 37%. Municipal tap water was added to the sandbox to produce a 40.5 cm thick saturated zone with a 10 cm unsaturated zone (i.e., total sand thickness of 50.5 cm). The surface boundary temperature was controlled by placing the sandbox in an environmental chamber capable of producing air temperatures between -4°C and 30°C. The temperature in the environmental chamber was varied during six temperature cycles that were between 5 and 11 days in length. The evaporative loss of water from the system, which never exceeded 2 cm over a two day period (i.e., < 5% of the total water in the saturated zone), was controlled by adding water to the sandbox as required. Water added to the system was at the ambient temperature within the environmental chamber.

Three piezometers (i.e., a screened drive-point connected to a standpipe) were installed in the sandbox. Each piezometer drive-point was 30.5 cm in length and constructed of 304 stainless steel that had a 15 cm slotted section centered along its length. The slotted section was wrapped 1.5 times using a 240R geotextile fabric (Terrafix® Geosynthetics Inc., Ontario), which was over wrapped with a stainless steel mesh. Each drive-point was fitted with a 69.5 cm long, 3.34 cm OD standpipe to produce an overall piezometer length of 100 cm. Approximately 50% of each standpipe extended above the sand surface and was directly exposed to air temperature changes in the environmental chamber. A 50% exposure of standpipe material was considered a potential worst-case scenario. Three different standpipe materials were investigated: schedule 40 steel (0.5% carbon content); schedule 40 steel (0.5% carbon content) wrapped with styrofoam pipe insulation; and schedule 40 PVC. The approximate thermal properties of all materials used in the laboratory experiment are provided in Table 1.

Sand surface (SS) temperatures, *in situ* water table (WT) temperatures, *in situ* groundwater temperatures (P in brackets indicates an *in situ* location associated with a corresponding paired piezometer), and water temperature in the steel (S), insulated steel (IS), and PVC piezometers were measured using Minilog TX temperature probes (Vemco Limited, Nova Scotia). These probes have a 3 mm diameter stainless steel sensor located at the tip of a 10 cm long, 2 cm OD PVC probe housing. All of the probes used in the laboratory experiment were programmed for synchronized time triggered temperature recordings every 15 minutes.

Table 1. Thermal conductivity (k), density (ρ), volumetric heat capacity (C), and thermal diffusivity (α) of the materials used in the laboratory experiment. Note: the thermal properties are reported for a temperature of 20°C. [a,b]References.

Material	k (W/m K)	ρ (kg/m^3)	C (10^6 J/m^3 K)	α (m^2/s)
Air	0.025	1.29	0.001	1938
Water	0.6	1000	4.180	14
Dry sand	0.35	1600	1.270	28
Saturated sand	2.7	2100	2.640	102
Wood	0.4	780	0.187	214
Steel (0.5% C)	54.0	7833	3.642	1483
Stainless steel 304	16.0	7900	3.950	405
PVC	0.16	1300	1.950	8
Pipe insulation	0.03	50	0.100	30
Styrofoam	0.01			

[a]http://www.hukesflux.com/thermal%20conductivity/thermal.htm
[b]http://www.engineersedge.com/properties_of_metals.htm

A probe was installed in each piezometer by suspending it from a stainless steel wire attached to an eyelet in the vented PVC cap. The sensor in each piezometer was at approximately the same elevation (± 0.25 cm) and was situated at the center of the drive point screened section (Figure 1). Paired with each piezometer probe was an *in situ* probe. The three *in situ* probes were installed in the sandbox prior to adding the sand by suspending them from a string grid. The sandbox was then carefully filled with sand to enclose the *in situ* probes. Each *in situ* probes had identical boundary conditions to its paired piezometer probe. Temperatures at the SS and WT were measured using two probes at each elevation (labeled as probe 1 and 2).

2.2 Field Experiment

A field experiment was conducted to determine if temperatures measured in the subsurface are different based on access tube design. Shallow groundwater temperatures were measured in schedule 40 and schedule 80 standpipe piezometers (P) paired with schedule 40 and schedule 80 sealed well points (SW) (i.e., a sealed pipe filled with water and air). All standpipes and well points have an OD of 3.34 cm.
The four instruments were installed within a 1 m^2 area in the Catamaran Brook basin in central New Brunswick (46° 52.7' N, 66° 06.6' W). The instruments were installed in a floodplain that is characterized by a shallow unconfined aquifer. The 5 m thick aquifer materials are sand and gravels that have a geometric mean hydraulic conductivity of 9.0×10^{-6} m/s. Estimated average linear groundwater velocities at the site are 0.2 m/d, and groundwater temperature is influenced by the recharge of precipitation and

groundwater-stream interactions with the brook located 10 m to the north of the instruments.

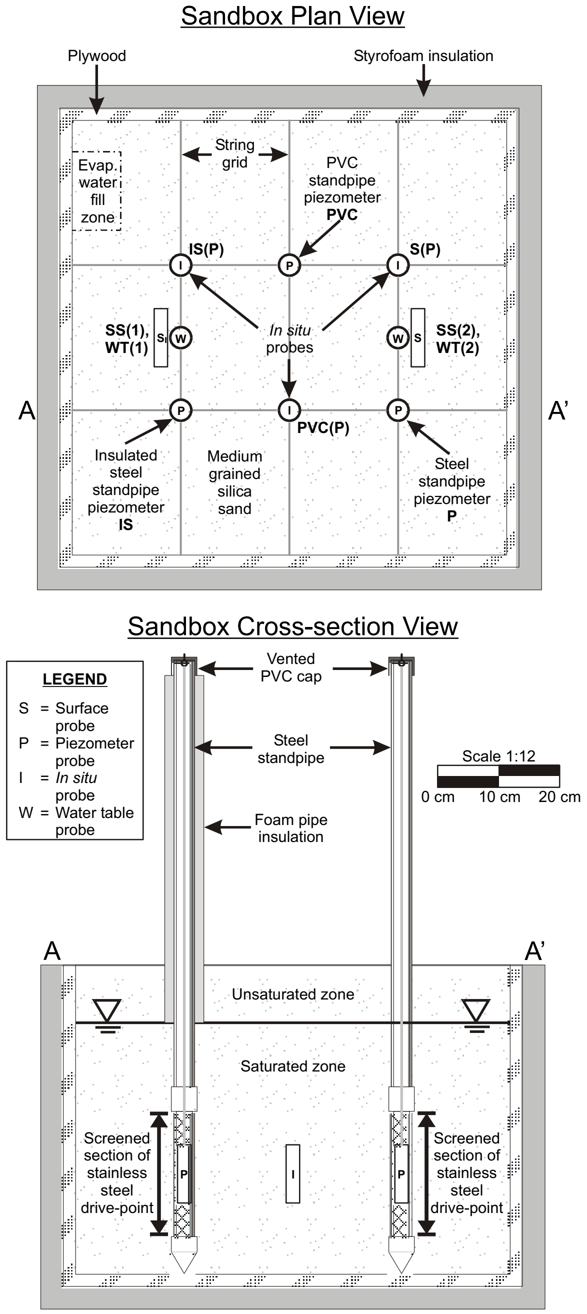

Figure 1. Plan view and a cross-sectional view of the laboratory set up used to investigate the effect of piezometer materials on subsurface temperature.

The field installation is shown in Figure 2. The piezometers and sealed wells were installed using a gasoline powered demolition hammer and a drivehead system designed by the authors. Each of the instruments had approximately the 0.46 m of exposed steel pipe. PVC standpipes were not used because PVC would not withstand being driven into the relatively hard aquifer materials. Temperature probes, similar to those used in the laboratory experiment, were installed in each well by suspending them with a wire from an eyelet installed in a PVC well cap. When comparing the individual installations, the elevation of the sensor above the bottom of the instrument was about the same (i.e., ± 0.02 m; Figure 2). Caps for piezometers were vented to the atmosphere with a 2 mm diameter hole. The sealed well points were filled with water to a depth of 10 cm below the ground surface (i.e., with temperature probe installed; Figure 2). The well points were not completely filled with water in order to avoid preferential heating/cooling of the water contained in the well above, at, or near the ground surface. The well points were sealed at connection points using silicon plumber's tape and epoxy. Water levels in the piezometers fluctuated by approximately 15 cm during the course of the experiment. All probes were programmed for hourly synchronized time triggered temperature recordings between 28 May 2003 and 14 November 2003.

2.3 Temperature Probe Calibration and Data Analysis

As received from the manufacturer, the temperature probes have a measurement range of -5°C to 35°C with a 0.2°C resolution and a ± 0.3°C accuracy. For this study the probes were calibrated using the three-step calibration procedure of Steinhart and Hart (1968). Temperatures measured by the probes were compared to the temperature measured by a set of National Institute of Standards and Technology (NIST) traceable mercury thermometers accurate to ± 0.1°C. A Microsoft® Excel spreadsheet program, designed by the authors, was used to calculate the Steinhart-Hart calibration coefficients and to correct the temperature measured by the probes to coincide with the NIST referenced thermometers. Using these calibration procedures, probe temperature resolution was improved to 0.156°C and the accuracy to ± 0.156°C.

Temperature measurements from the laboratory experiment and field experiment were analyzed using two statistical software packages. Minitab™ Release 13.20 was used for basic statistics, regression, and paired *t*-test calculations. *ANOVA* analysis was also performed on the field data. The time series analysis package ASTSA (Shumway and Stoffer 2000) was used to calculate the cross-correlation functions. For the laboratory experiment, the data was analyzed as an entire data set (i.e., all six temperature cycles combined) and as six separate data sets (i.e., each temperature cycle independently). For the field experiment, statistical analyses were performed on four paired data sets: 1) P(40) and SW(40); 2) P(80) and SW(80); 3) P(40) and P(80); and 4) SW(40) and SW(80).

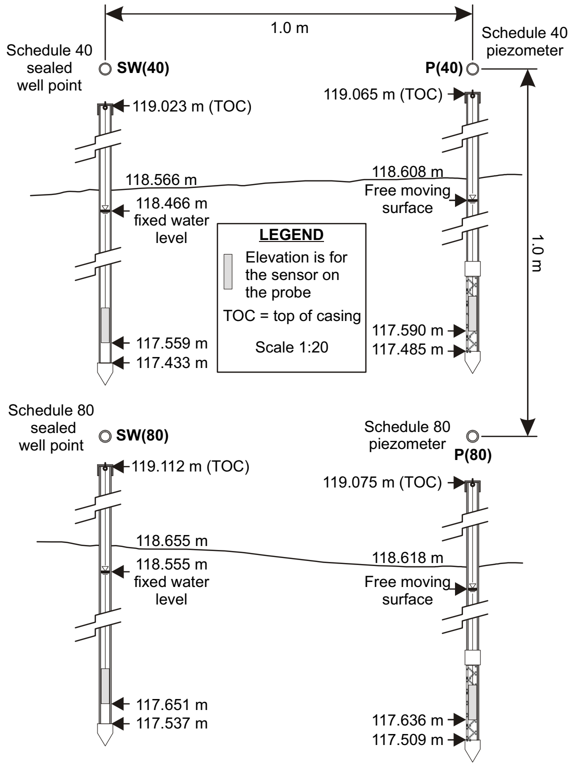

Figure 2. Plan view and cross-sectional view of the field site setup used for testing different groundwater instrument configurations.

3. RESULTS AND DISCUSSION

3.1 Laboratory Experiment

A plot of the temperature change during the six-cycle 54 day laboratory experiment, as measured by SS(1) and an *in situ* temperature probe, PVC(P), is shown in Figure 3. Basic descriptive statistics for each measurement location during the entire six-cycle laboratory experiment are provided in Table 2.

Temperatures measured by the two SS probes were perfectly positively correlated during the entire experiment (Pearson correlation, $r = 1.000$, sample probability, $p = 0.0001$). When the SS data were analyzed as six independent data sets the measurements between the two probes were highly positively correlated ($r > 0.975$, $p = 0.0001$). Temperature fluctuations measured at WT(1) and WT(2) were considerably dampened because porous media behaves as a low pass filter to heat and only retains long-term temperature changes (Beltrami and Chapman 1994). The temperatures measured by the two WT probes were perfectly positively correlated when the complete data set was analyzed ($r = 1.000$, $p = 0.0001$). For the six separate temperature cycles the correlation was never < 0.998 ($p = 0.0001$).

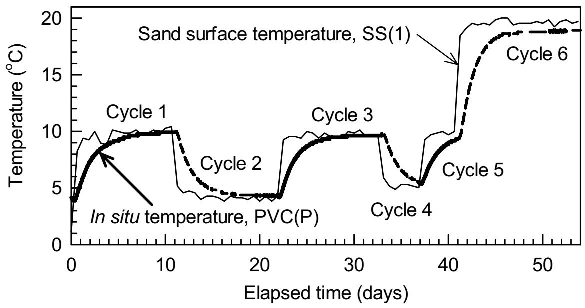

Figure 3. General temperature change for a sand surface temperature probe, SS(1), and an *in situ* temperature probe, PVC(P), during the six-cycle 54 day laboratory experiment.

Table 2. Basic descriptive statistics calculated for each temperature measurement location during the entire experiment (n = 5189 measurements/probe). Note: SD = standard deviation, Min = minimum, and Max = maximum.

Probe	Mean (°C)	SD (°C)	Min (°C)	Max (°C)
SS(1)	10.6	5.49	-0.7	20.3
SS(2)	10.6	5.54	-0.7	20.3
WT(1)	10.0	4.90	3.4	18.8
WT(2)	10.0	4.87	3.3	18.9
S	10.0	4.81	4.0	18.9
S(P)	10.0	4.81	4.0	19.0
IS	10.0	4.83	3.8	18.9
IS(P)	9.9	4.81	3.8	19.0
PVC	9.9	4.81	3.9	18.9
PVC(P)	10.0	4.81	3.9	18.9

The mean temperature and standard deviation for the S and S(P) probes were identical for the entire study period and were perfectly positively correlated ($r = 1.000$, $p = 0.0001$). Analysis of each individual temperature cycle yielded a mean difference between the S and S(P) probe of $\leq 0.1°C \pm 0.11°C$ ($p = 0.0005$) and the correlation did not fall below 0.998 ($p = 0.0001$). Temperatures measured by the IS and IS(P) probes were also perfectly positively correlated ($r = 1.000$, $p = 0.0001$). Individual temperature cycle analysis yielded a difference between the IS and IS(P) means of $\leq 0.1°C \pm 0.08°C$ ($p = 0.0005$) and a correlation of not < 0.998 ($p = 0.0001$). The temperatures measured by the PVC and PVC(P) probes closely matched one another for the entire study period ($r = 1.000$, $p < 0.0001$). Analysis of each of the six individual temperature cycles showed mean temperature differences between PVC and PVC(P) to be

$\leq 0.1°C \pm 0.06°C$ ($p = 0.0005$) and $r \geq 0.999$ ($p = 0.0001$).

Figure 4 shows additional statistical analysis results for temperature Cycle 1 of the laboratory experiment for the three piezometer probes and three *in situ* probes ($n = 1057$ measurements/probe). There was a high Pearson correlation ($r = 0.999$) between the temperatures measured in each piezometer and the paired *in situ* probe. Regression analysis of the paired data yielded small standard errors ($SE \leq 0.08$) and high coefficient of determination values ($r^2 \geq 0.998$). Cross-correlation analysis yielded zero lag time for each paired data set and high cross-correlation functions ($CCF \geq 0.999$). The results for the other five temperature cycles are similar to those shown in Figure **4**.

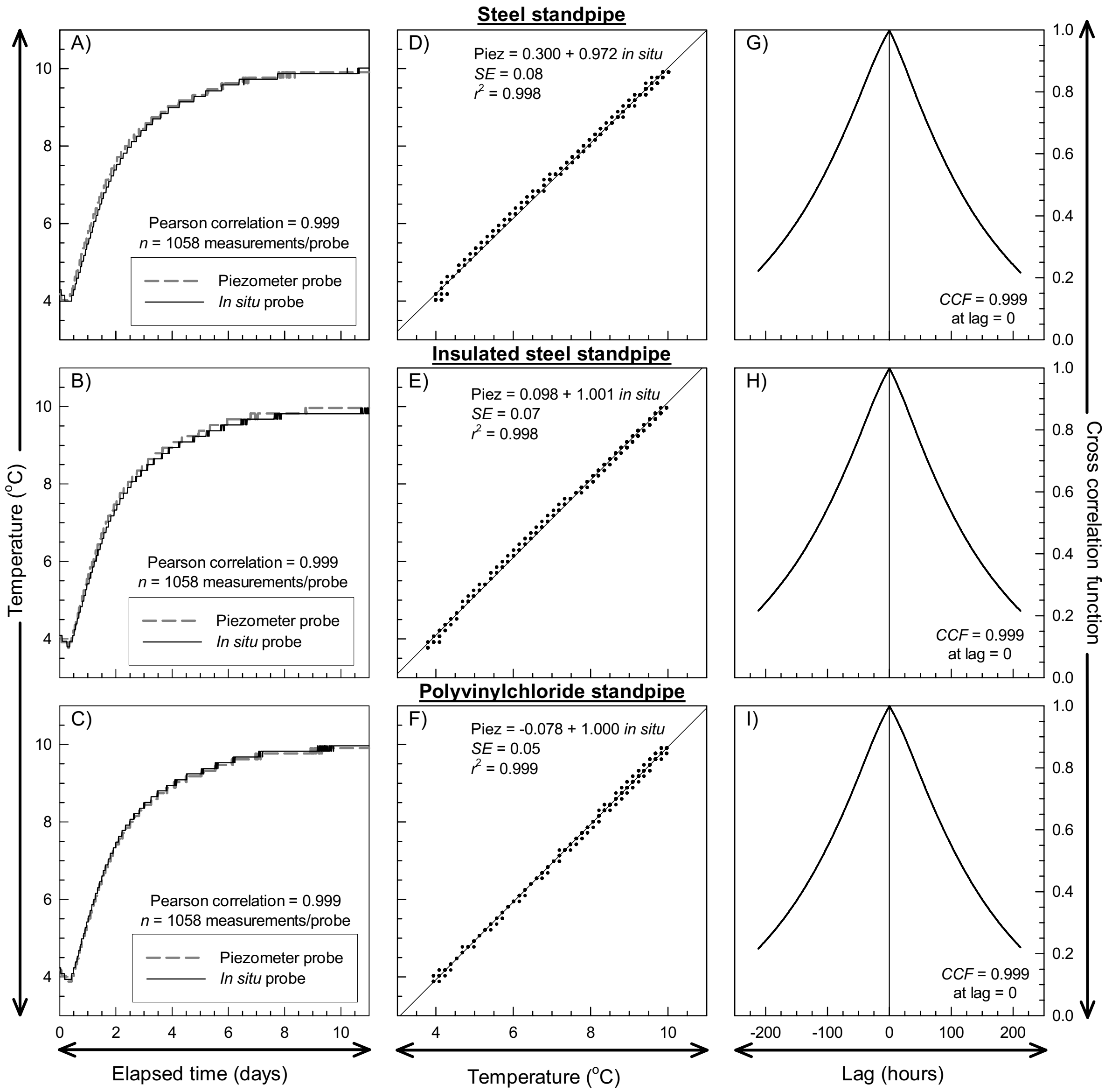

Figure 4. Temperature data and statistical analysis results for temperature Cycle 1 of the laboratory experiment. Panels A), D), and G) show the results for the steel standpipe piezometer and the paired *in situ* probe. Panels B), E), and H) show the results for the insulated steel standpipe piezometer and the paired *in situ* probe. Panels C), F), and I) show the results for the PVC standpipe piezometer and the paired *in situ* probe.

Paired *t*-tests were performed on temperature data collected during the entire experiment ($n = 3$ *t*-tests) and during the six individual temperature cycles ($n = 24$ *t*-tests) to determine if differences between means of the paired temperature probes were significant. All *t*-tests performed were statistically significant ($p = 0.05$). Although the results suggest that differences in the means are significant, the differences are of a magnitude that has no practical significance (Daniel, 1998). For example, all of the differences between the mean values are ≤ 0.1°C ± 0.08°C, which is less than the improved resolution of the temperature probes.

The analysis of the laboratory results shows that the temperature measured by the piezometer probes were equivalent to their paired *in situ* probes. Results from the *t*-tests suggest that small temperature differences existed between the measurement locations and that these differences were statistically significant; however, because these differences are less than the temperature resolution of the probes they are not practically significant. Therefore, given the probe resolution of 0.156°C, the results of the laboratory experiment demonstrate that the presence of a standpipe does not preferentially conduct heat into the shallow subsurface.

3.2 Field Experiment

Hourly subsurface temperatures measured in the two piezometers and two sealed wells are shown in Figure 5. A 90 day period when temperatures increased (i.e., 28 May 2003 to 25 August 2003) and a 78 day period when subsurface temperature decreased (i.e., 29 August 2003 to 14 November 2003) comprise the 168 day experiment ($n = 4063$ measurements/probe). A four day gap in the data exists between the two temperature periods because the probes were removed from the instruments for data retrieval. A summary of the basic statistics for each measurement location is provided in Table 3.

Subsurface temperatures measured in the two schedule 40 standpipe instruments are shown in Figure 5A. Although the two series follow the same trends, the mean temperature measured in P(40) was 0.3°C ± 0.35°C warmer than the temperature measured in SW(40). The maximum temperature measured in each instrument occurred on 14 August 2003. The two subsurface temperatures were highly positively correlated during the experiment ($r = 0.987$, $p = 0.0001$) and the difference in mean temperature between the two locations was greater during the increasing temperature period (i.e., 0.6°C ± 0.15°C) than during the decreasing temperature period (i.e., 0.0°C ± 0.24°C). No difference was calculated for *r* between the two periods. On 23 October 2003 the subsurface temperature measured in P(40) dropped below the temperature measured in SW(40) for the first time and remained below to the end of the experiment.

The subsurface temperatures measured in the two schedule 80 standpipe installations are shown in Figure 5B. Compared to the schedule 40 standpipe installations, the temperatures measured in these two instruments more closely match one another. The temperature measured in P(80) was 0.2°C ± 0.19°C warmer than in SW(80). The temperatures, during the 168 day study, were highly positively correlated ($r = 0.996$, $p = 0.0001$); a greater difference in temperature existed during the increasing temperature period (0.3°C ± 0.17°C) than during the decreasing temperature period (0.0°C ± 0.11°C). There was no difference present in *r* for the two temperature measurement periods. The maximum temperature for each installation occurred on 23 August 2003, which is about one week later than that measured for the schedule 40 instruments. The subsurface temperature measured in P(80) fell below the temperature measured in SW(80) on 2 November 2003 and remained below for the duration of the experiment.

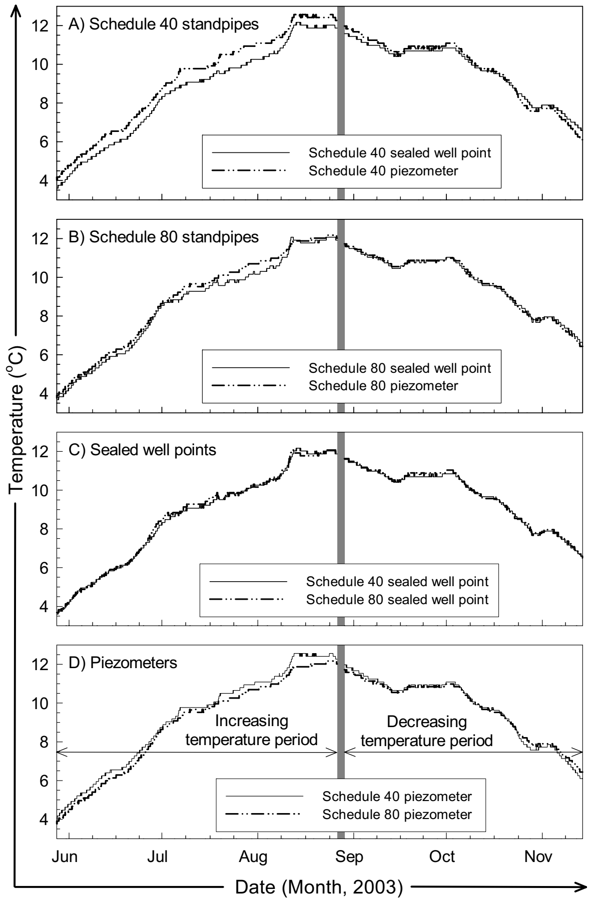

Figure 5. Temperatures measured in the A) schedule 40 instruments, B) schedule 80 instruments, C) sealed well points, and D) piezometers. Note: the grey patch between the two temperature periods represents a data retrieval period.

The subsurface temperatures measured in the two sealed well points are compared in Figure 5C. Both locations had the same mean and standard deviation. Additionally, these two locations had the highest *r* of

0.999 ($p = 0.0001$), which was the same during both temperature periods.

Subsurface temperatures measured in the two piezometers are plotted in Figure 5D. The mean temperature calculated for P(40) was 0.1°C ± 0.22°C warmer than the mean temperature calculated for P(80). The temperature measured in the two instruments was highly positively correlated during the entire field experiment. Temperature was greater in P(40) until 22 October 2003 when it fell below P(80). There was a greater temperature difference between the two instruments during the increasing temperature period (0.3°C ± 0.14°C) than during the decreasing temperature period (0.0°C ± 0.17°C). The temperatures were almost perfectly positively correlated during both periods (i.e., 0.999, $p < 0.0001$).

Table 3. Basic descriptive statistics calculated for each temperature measurement location during the field experiment ($n = 4063$ measurements/probe).

Location	Mean (°C)	SD (°C)	Min (°C)	Max (°C)
SW(40)	9.1	2.14	3.6	12.2
P(40)	9.4	2.18	4.0	12.6
SW(80)	9.1	2.14	3.7	12.1
P(80)	9.3	2.14	3.8	12.2

Cross-correlation plots for the four paired data sets are shown in Figure 6 for three analysis periods. All paired subsurface temperatures responded similarly to temperature changes. All plots have a lag time of zero and the *CCF* values are > 0.9870.

One-way unstacked *ANOVA* tests were performed on all of the subsurface temperature measurements made during the entire experiment. For a level of significance, α, of 5% the results yielded evidence of a statistically significant variation between certain subsurface measurements ($F = 22.41$; $p = 0.0005$; $df_{v1} = 3$; $df_{v2} = 16248$). The results showed that SW(80) and SW(40) were not statistically different from one another. P(80) and P(40) were statistically different from one another and the other two instruments. The same conclusion was obtained when the data sets were analyzed only during the increasing temperature period ($F_{0.05} = 28.47$; $p = 0.0005$; $df_{v1} = 3$; $df_{v2} = 8708$). When the data sets were analyzed strictly during the decreasing temperature period the *ANOVA* results showed no statistical significance in the tests ($F_{0.05} = 0.53$; $p = 0.664$; $df_{v1} = 3$; $df_{v2} = 7536$).

A series of *t*-tests were performed on the paired data sets for the entire field experiment ($n = 4$) and for the increasing and decreasing temperature periods ($n = 8$). The results yield differences in the means to be statistically significant in all cases. During the entire experiment the mean difference between P(40) and P(80) was 0.16°C, which is equivalent to the resolution of the probes. The difference between the two schedule 40 instruments was also statistically significant and the difference was slightly greater than twice the logger resolution at 0.35°C. Although all of the *t*-tests were considered statistically significant only 33% are deemed practically significant (Table 4). Tests that are practically significant are those tests where the difference between the means is greater than the temperature probe resolution.

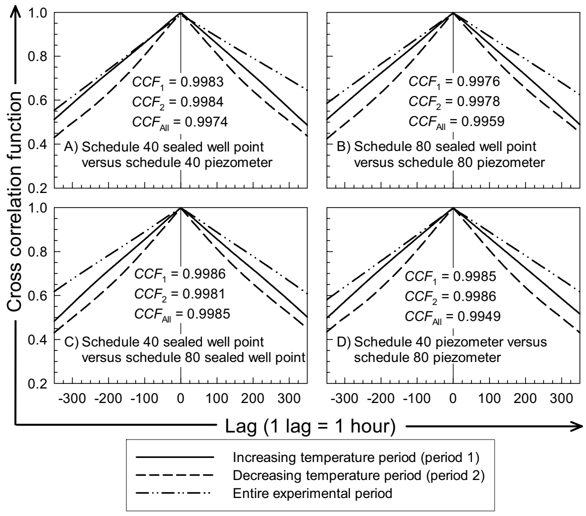

Figure 6. Cross-correlation functions for A) the two schedule 40 instruments, B) the two schedule 80 instruments, C) the two sealed well points, and D) the two piezometers during the three analysis periods.

Table 4. Differences in the means for the data collected during the field experiment. Note: shaded cells with bold entries indicate *t*-test results where the difference in the means is statistically and practically significant.

	All Data (°C)		↑ T (°C)		↓ T (°C)	
	SW(80)	P(40)	SW(80)	P(40)	SW(80)	P(40)
SW(40)	0.04	**0.35**	0.04	**0.62**	0.05	0.05
P(80)	0.15	0.16	**0.26**	**0.31**	0.01	0.01

The statistical analysis results show that the temperatures measured in the different groundwater instrument configurations were similar. Temperatures measured in SW(40) and SW(80) show no differences that might be attributed to the steel standpipe wall thickness. Mean differences in temperature measured between the sealed well points and piezometers were 0.26°C and 0.62°C during the warming period; however, differences between sealed well points and piezometers were not observed during the 78 day cooling period. When P(40) and P(80) temperatures are compared, a mean difference of 0.31°C is observed during the warming period. Since such a difference cannot be attributed to differences in wall thickness (based on SW results), it must reflect local spatial (or temporal) variability in groundwater flow or sediment thermal properties. The differences in temperatures observed between sealed well points and piezometers are therefore also expected to be, in part, the result of natural variability at the scale of the field experiment. Given this complicating factor and the results for the latter half of the experiment, it appears that sealed well points and piezometers give essentially the same temperatures.

4. CONCLUSIONS

The laboratory experiment results show that the different piezometer standpipe materials tested do not cause preferential conduction of heat into the shallow subsurface. Temperatures measured within the screened section of stainless steel piezometers connected to steel and PVC standpipes were equivalent to paired *in situ* temperatures. Results from the field experiment suggest that, in the case of low velocity groundwater systems, the temperature measured in piezometers and sealed well points are comparable.

5. ACKNOWLEDGEMENT

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