PROCEEDINGS OF A U. S. GEOLOGICAL SURVEY WORKSHOP ON THE APPLICATION AND NEEDS OF SUBMERSIBLE PRESSURE SENSORS, DENVER, COLORADO, JUNE 7-10, 1994

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PREFACE

The U.S. Geological Survey (USGS) conducted a Submersible Pressure Sensor workshop at the USGS National Training Center in Lakewood, Colorado, June 7 - 10, 1994, oriented towards the application and needs of pressure sensors in ground-water investigations. Thirteen of the 23 attendees gave presentations that covered the following topics: (1)specialized and routine applications of submersible pressure sensors, (2)pressure-sensor instrumentation problems and needs, (3)use and storage of pressure-sensor data, and (4)needs associated with training and technology transfer. In addition to the presentations and the resulting abstracts and papers that are presented in these proceedings, panel and open-forum discussions were conducted at the workshop on each of the topics.

These proceedings are intended to supplement information presented at the two previous USGS pressure-sensor workshops published as (1) Proceedings of a pressure transducer-packer workshop, June 25-28, 1991: U.S. Geological Survey Open-File Report 93-71, by Latkovich, V.J., 1993, and (2) Proceedings of a U.S. Geological Survey pressure-sensor workshop, Denver, Colorado, July 28-31, 1992, Open-File Report 94-363, by Wilbourn, S.L., 1994. All three proceedings volumes are intended for broad distribution and use in planning the many and varied applications of pressure sensors within the USGS.

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CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATIONS AND ACRONYMS

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft.)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile^2 (mi^2)	2.590	kilometer^2 (km^2)
foot per second (ft/s)	0.03048	meter per second (m/s)
foot^3 per second (ft^3/s)	0.02832	meter^3 per second (m^3/s)
pound (lb)	0.4536	kilogram (kg)
millions of gallons per day (MGD)	0.04381	meter^3 per second (m^3/s)
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

Temp °F = 1.8 (temp °C) + 32

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a geneal adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929. Abbreviations and acronyms used in this report:

21X	Campbell Scientific 2X Data Logger
ADAPS	Automatic Data Processing System
CR-10	Campbell Scientific CR-10 Data Logger
DAS	Dry Air System
DBLS	Depth Below Land Surface
DCP	Data-Collection Platform
DPS	Digital Pressure Sensors
DRGS	Direct Readout Grond Station
EAFB	Edwards Air Force Base
H-300	Design Analysis Water Log H-300 Pressure Sensor
HIF	Hydrologic Instrumentation Facility
LSD	Land Surface Datum
NTS	Nevada Test Site
NWIS	National Water Information System
PFC	Portable Field Computer
PSI	Pounds Per Square Inch
PVC	Poly-vinyl Chloride
r^2	Statistical Coefficient of Determination
RS-232	EIA Standard - Interface between data terminal equipment and data circuit - terminating equipment employing serial binary data interchange
SCADA	Supervisory Control and Data Acquisition
SDI-12	Serial Digital Interface (1200 baud)
USGS	United States Geological Survey

WORKSHOP PROCEEDINGS

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Conversion of Transducer Data to Water Levels Using the National Water Information System (NWIS)

By Douglas J. Burkhardt[1]

Pressure transducers are being used to monitor water levels in the Yucca Mountain area, Nevada. The data will be used to help evaluate the suitability of the area for storing high-level nuclear waste. In the early years of the saturated zone studies, transducer output (millivolts) from boreholes was converted to water-level altitude (in meters above sea level) using software written by project staff. Currently a technique for using the U.S. Geological Survey's National Water Information System (NWIS) is being used to convert transducer output to water levels.

The Automated Data Processing System (ADAPS) sub-system of the National Water Information System (NWIS) was created to process, store, and retrieve water data. The software was originally created mainly for surface water data, but may be used for other types of data. This software's flexibility allows various types of data processing to be performed within the database. The water-level data collected at Yucca Mountain are sent via satellite from data collection platforms (DCP's) directly into ADAPS. Data are collected hourly and transmitted every four hours to the ADAPS sub-system. Data manipulation within the ADAPS system is required to convert transducer output to water levels.

The conversion of transducer output to water levels involves several steps. When the transducer is installed, water-level altitude is determined using a steel tape or multi-conductor cable. A calibration factor that relates change in transducer output to a change in depth of transducer submergence is then determined. The transducer is lowered to a predetermined depth below water-level surface, termed the "setpoint," and the transducer output is then recorded. If the transducer output at the setpoint remains constant over time and the calibration factor does not change, the conversion of data is a three-step process. First, the output of the transducer at the initial setpoint in millivolts is subtracted from the output data. The resulting millivolt value represents the change in transducer submergence depth (change in water level). This step is performed within ADAPS by using a linear variable datum correction. Secondly, the data are divided by the calibration factor, which converts the millivolt change to water-level change in meters. Lastly, the change in water level is added to the water-level altitude measured at the last calibration. These two steps are performed within ADAPS by using a standard rating table. A standard rating table is a generic equation in which the user supplies the coefficients. The rating table uses the calibration factor to convert the change in millivolts to a change in meters. Then the rating table adds the change in water level to the initial water level. All calculations in the conversion process are completed entirely within ADAPS.

Transducer output does not always remain constant at the setpoint due to drift, and calibration factors tend to change to some degree. These variable factors cause the conversion of millivolts to water levels to be more complex. For example, the transducer output may change from 10 millivolts to 11 millivolts at a constant setpoint or the calibration factor at

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the beginning of a period may be different from the ending calibration factor. These types of problems can be accurately accounted for with frequent and reliable calibration, setpoint, and water-level-measurement data.

The first type of drift is setpoint drift. The effect of this drift is to give changes in the record that are transducer related not water-level changes. The first step to remove this type of drift is to determine what water-level change occurred. Manual water-level measurements are assumed to be more accurate than hourly transducer measurements. At the beginning and end of a period, a manual measurement is taken. The change in water level from beginning to end of the period is converted to millivolts using the calibration factor. This gives the expected change in the setpoint. The next step is to subtract the setpoint for the beginning of the period from the ending setpoint. This amount is the change in setpoint that occurred. Drift is the difference between the expected and the actual millivolt changes. If the ending setpoint is higher than the expected, the transducer had positive drift in that period. If the ending setpoint is lower than what was expected the transducer output drifted negatively.

ADAPS is used to account for this type of drift with a linear datum correction. This type of drift is assumed to be linear over time. At the beginning of a period, the initial setpoint is always used. The adjustment for drift is made at the end of the period. If a transducer has a positive drift over a period, the ending setpoint will equal the initial setpoint plus the amount of the drift. The effect of accounting for drift is to eliminate change not related to water-level fluctuation. Similarly, if the drift was determined to be negative, the ending setpoint will equal the initial setpoint minus the amount of the negative drift.

The other type of drift is calibration factor drift. The effect of this type of drift is to give an inaccurate millivolts-per-meter conversion factor for the data. The amount of drift is determined by subtracting the ending calibration factor from the beginning calibration factor. It is assumed the calibration factor drifts linearly over time. This is accounted for in ADAPS by inserting additional rating tables. The drift is calculated for the whole period and divided by the number of months within the period. If the calibration factor has drifted significantly enough to change every month, a new rating is entered for each month. If the drift is not enough to change the calibration factor, the same equation is used for the entire period. To account for either type of drift, a beginning and ending setpoint, water-level measurement, and calibration factor is essential.

High-accuracy Measurements With Inexpensive Pressure Sensors—assembly, Calibration, and Use

By M.C. Carpenter[1]

Inexpensive pressure sensors can be soldered to inexpensive cable, potted in waterproof housings, and submerged in water to measure water-level changes in wells and piezometers, pore-pressure changes in saturated sediments, and soil-moisture tension with an accuracy of ±0.03 percent or better. A useful sensor that can have water in the pressure port is the Motorola MPX2200AS[2]. This absolute-pressure sensor has a range of 21 meters of water. Because atmospheric pressure is about 10 meters of water, this sensor can be used to measure submergence of as much as 11 meters of water. Measurement of submergence is done using one sensor as a barometer and another sensor under water. The difference in pressure between the sensors is submergence. Differential-pressure sensors that can be used with water in both ports include the Honeywell Micro Switch 24PC and 26PC series. Full-scale pressure spans range from 0.3 to 20 meters of water. Differential sensors require a vent tube from the reference port to the atmosphere but do not require a barometer for adjustment to submergence. A barometer, however, is a useful ancillary sensor when measuring ground-water levels because the barometric effect on water levels in wells and piezometers can be as much as 0.2 meters.

A rugged and inexpensive housing for these sensors consists of a PVC-pipe coupling and two plugs (fig. 1). The bottom plug is center-drilled with a letter "D" bit (6.248-millimeter diameter) for a pressed fit that allows the pressure port to stick out the bottom of the housing. The top plug is drilled for cable feedthrough, vent-tube feedthrough (differential sensors only), and potting relief. The cable (Belden 8723) and vent tube (3- to 5-millimeter nylon tubing) are pressed through the plug and attached to the sensor. The pressure port is pressed through the bottom plug, and the contact between the PVC and pressure port is sealed with cyanoacrylic glue, such as Locktite Prism 401 with 704 primer. The bottom plug is glued into the coupling, the cavity is filled with potting compound, such as TAP 1-1 (TAP Plastics, Dublin, California), and the top plug is pressed into place allowing excess potting compound to flow out the relief hole. TAP 1-1 has been observed to have greater than 10 gigaohms resistance after 3 years in water. If TAP 1-1 is used, the components should be warmed to at least 40° Celsius before mixing.

A common calibration procedure for pressure sensors uses a standpipe to obtain different values of submergence and a linear regression or straight-line fit. The equation is:

$$V = a + bP, \tag{1}$$

in which V is sensor output (the dependent variable), in millivolts; P is pressure (the independent variable), in meters or feet of water; and a and b are regression coefficients. Equation 1 is solved for P giving:

$$P = \frac{V - a}{b}. \tag{2}$$

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[2] Use of trade names in this abstract is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

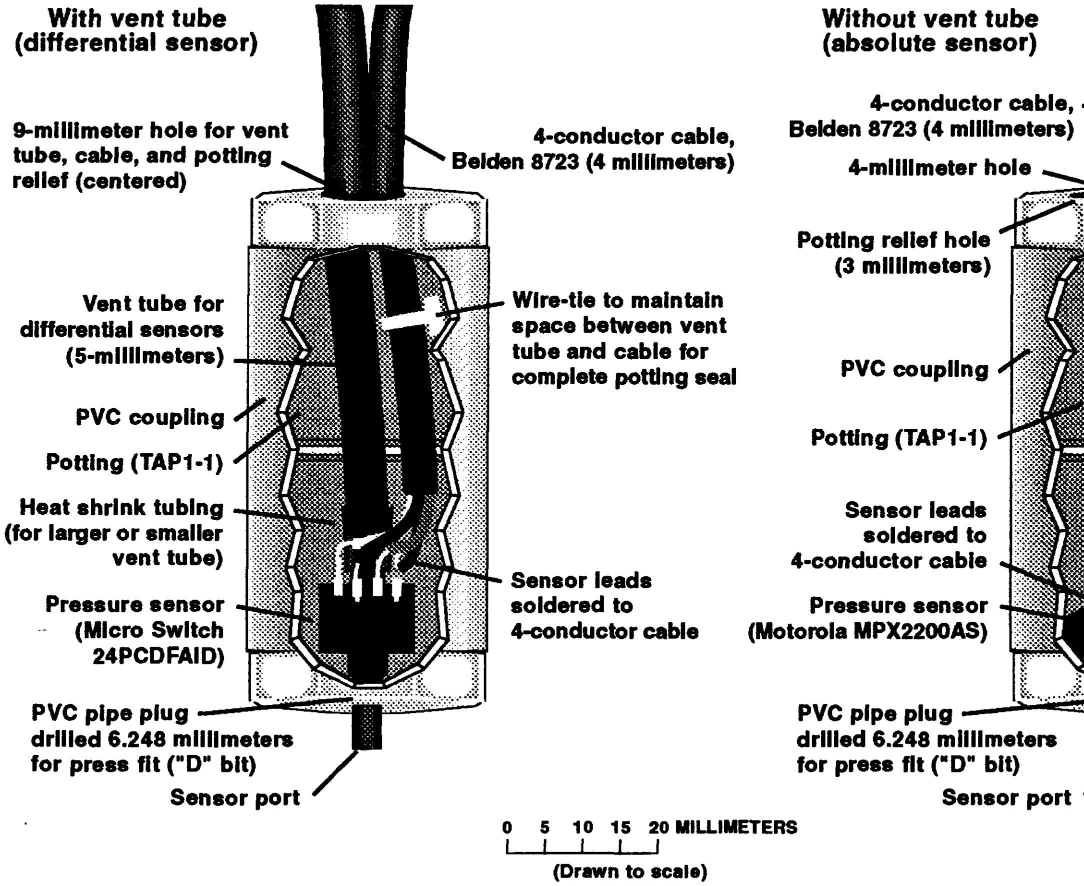

Figure 1. Pressure-sensor housing.

In the calibration procedure, the variables *P* and *V* are commonly switched, giving:

$$P = a' + b'V, \qquad (3)$$

in which $a'=1/b$ and $b'=-a/b$ from equation 1. This procedure is statistically incorrect because independent and dependent variables are not interchangeable. As a practical matter, however, when the r^2 value (coefficient of determination) is 0.9999 or higher, the eventual coefficients that are programmed into the data logger are identical.

The problem with linear regression for calibration of pressure sensors is that the procedure gives the false appearance of a good fit while leaving large residual errors. In fact, the r^2 for the linear regressions for sensors M66, M68, and M69 range from 0.99998 to 0.999994 (fig. 2), although errors of as much as 30 millimeters exist between the calibration points and the individual linear-regression equations (fig. 3).

A more complicated but entirely manageable procedure reduces the residual error by an order of magnitude. The pressure sensors are calibrated at five pressures at each of three temperatures in a water bath in a Nalgene Dewar flask using a Paroscientific 760 field standard, a MityVac hand pump, and a manifold that distributes pressure to several sensors. These components are connected by plastic tubing and Swagelok fittings. A Campbell Scientific CR-10 data logger collects data from the pressure sensors, Paroscientific standard, and Campbell Scientific 107B

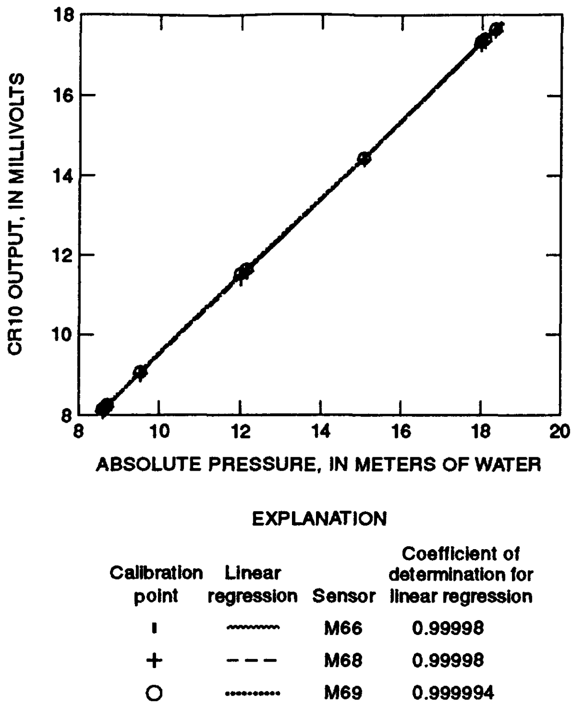

Figure 2. Linear-regression calibration for sensors M66, M68, and M69. No distinction can be made between the calibration points and the regression lines. Thus, this type of representation gives the false appearance of a good fit.

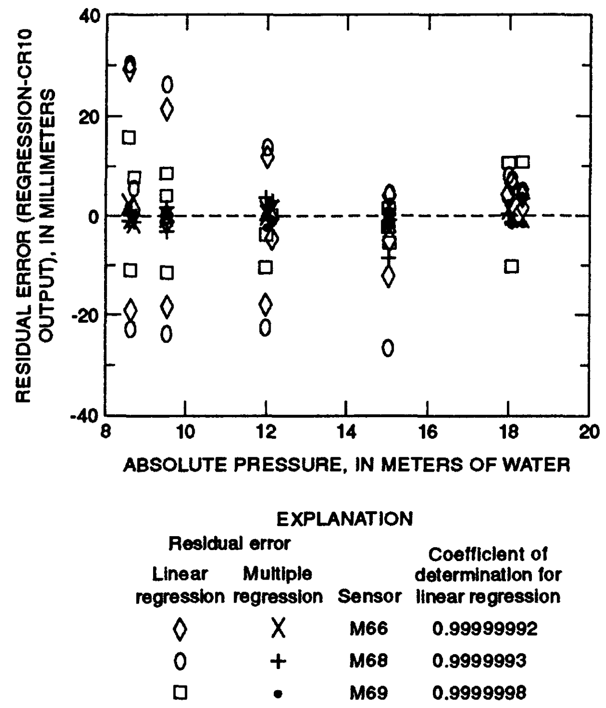

Figure 3. Comparison of residual errors from multiple regression with residual errors from linear regression. Error is reduced from ±30 millimeters to ±3 millimeters.

temperature sensors inside the manifold and in the water bath. This calibration procedure produces recorded values of voltage for ranges in pressure and temperature.

Multiple regression is used to determine the calibration equation for each pressure sensor. An equation that can reduce residual error with respect to the standard to ±0.03 percent over the calibration range of 10 meters of water-level fluctuation is:

$$V = a + bP + cP^2 + dT + eT^2 + fTP, \qquad (4)$$

in which V is sensor output (the dependent variable), in millivolts; P is pressure (an independent variable), in feet or meters of water; T is temperature (an independent variable), in degrees Celsius; and a, b, c, d, e, and f are regression coefficients. Solving equation 4 for pressure gives:

$$P = \frac{-(fT+b)}{2c} \pm \frac{\sqrt{(fT+b)^2 - 4c(a+dT+eT^2-V)}}{2c}. \qquad (5)$$

With the exception of one outlier of 8 millimeters, using equation 4 reduces the error to 3 millimeters. The corresponding range of r^2 using equation 4 is 0.9999993 to 0.99999992. Equation 5 can be programmed into a data logger to give temperature-corrected output if a temperature sensor is installed with the pressure sensor or built into the housing for the pressure sensor.

The MPX2200AS absolute-pressure sensors were jetted into place along with temperature sensors beside screened piezometers in three sand bars along the Colorado River in the Grand Canyon to monitor changes in bank-storage, seepage erosion, and slumping processes from October 1990 to April 1994. Discharge of the Colorado River in the Grand Canyon is regulated by Glen Canyon Dam and has fluctuated from less than 85 to more than 800 cubic meters per second on a daily basis. Stage fluctuations have exceeded 3.4 meters on downstream sand bars. Water-level and barometric fluctuations of selected sensors at sand bar 43.1L during 1992 (fig. 4) illustrate the low level of drift and hysteresis in the pressure sensors. Sensors P48, P46, and P37 were successively shoreward from the water's edge, and sensor P44 was 3 meters below sensor P46. Water-level fluctuations attenuated with distance into the sand bar and exhibited vertical as well as horizontal time-lag effects.

Two periods of constant discharge provided an opportunity to compare drift among sensors. Maximum difference among eight pressure sensors from a constant-discharge period ending on April 22, 1991, to the constant-discharge period ending on October 13, 1992, was 20 millimeters or 0.1 percent of the 10-meter range per year. Four sensors agreed to 3 millimeters or the resolution of the sensor with the data logger. The peak-to-peak, short-term difference between barometric sensors (fig. 4) was 12 millimeters. Long-term drift of the

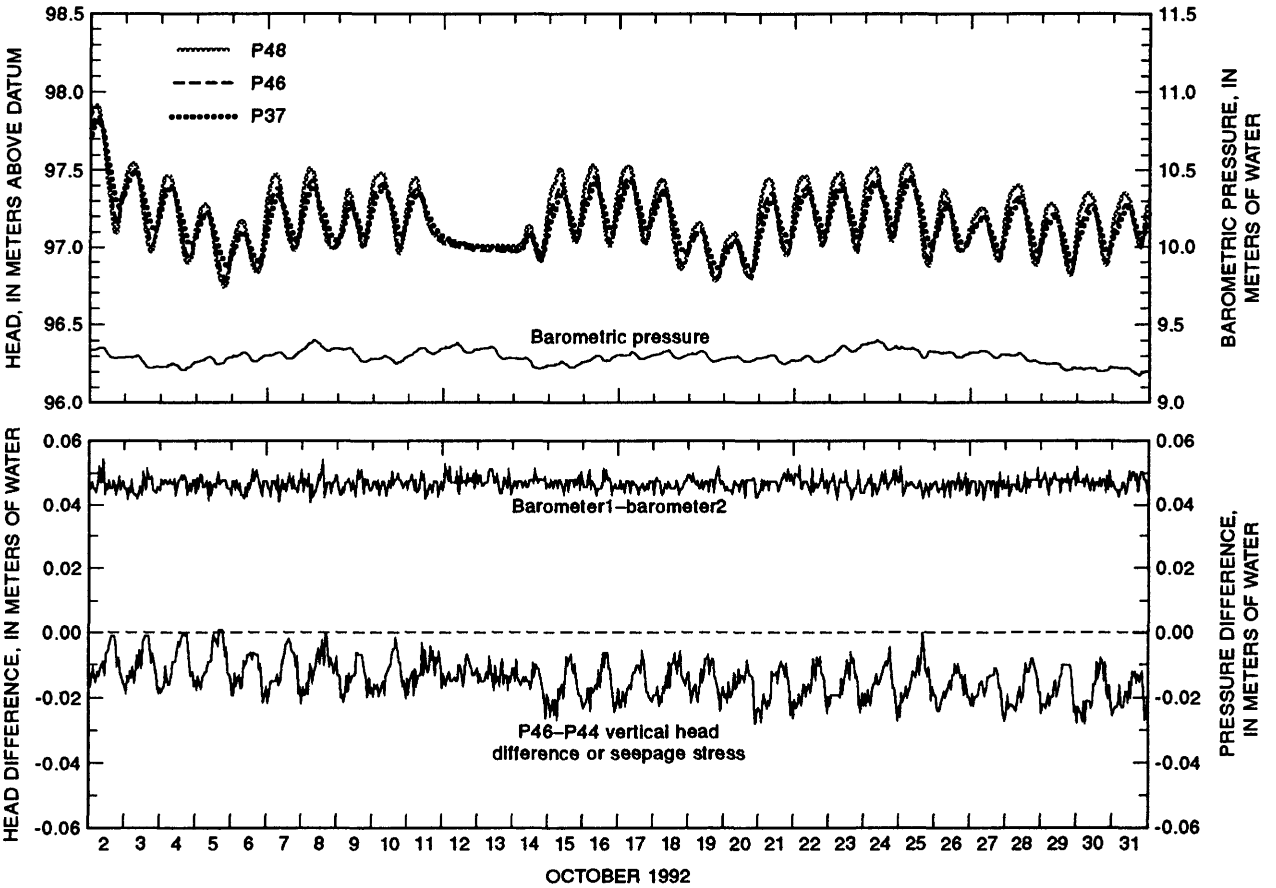

Figure 4. Water-level and barometric fluctuations at selected piezometers at sand bar 43.1L along the Colorado River in the Grand Canyon. Sensors P48, P46, and P37 are successively farther from the river's edge into the sand bar. Sensor P44 is 3 meters below sensor P46.

two barometric sensors also was 12 millimeters between April 1991 and October 1992.

Hysteresis is the difference between outputs of a sensor for identical inputs approached from positive and negative senses. Hysteresis is commonly called deadband and appears as clipping or truncation of peaks and troughs of highly variable time series. Specification of hysteresis for the MPX2200AS is 0.1 percent of full-scale output, or 20 millimeters. If hysteresis were 20 millimeters, the record of seepage stress (fig. 4) would exhibit pronounced flat peaks and troughs. Actual hysteresis appears to be no more than the sensor-data logger resolution of 3 millimeters or 0.014 percent of calibrated water-level fluctuation.

The MPX2200AS sensors provided high-accuracy data for more than 3 years when potted in inexpensive waterproof housings and submerged in saturated sand. Failure rate was about 15 percent. The sensors held calibration with a small amount of drift that was removed by measuring water levels in adjacent piezometers. Hysteresis was considerably less than the manufacturer's specification.

- PAGE 11 FOLLOWS -

GEOHYDROLOGIC DATA COLLECTION USING DESIGN ANALYSIS MODEL H-300 SUBMERSIBLE PRESSURE TRANSDUCERS AT EDWARDS AIR FORCE BASE, CALIFORNIA

By Lawrence A. Freeman[1]

The U.S. Geological Survey (USGS) began a study at Edwards Air Force Base (EAFB), California, in 1990. The study, a cooperative effort between the USGS and the U.S. Air Force, was requested by the Air Force to analyze the effects of ground-water withdrawals on ground-water levels and aquifer-system compaction on EAFB property. Geohydrologic applications of the collected water-level data include the study of aquifer-system mechanics as it relates to strain induced by natural phenomena such as earth tides, changing barometric pressure, and earthquakes.

Ground-water levels were recorded using three different types of water-level sensors: a float system with shaft encoder and two models of submersible pressure transducers. The float system did not operate properly, even at shallow depths, because of the friction between the floats and the 2-inch poly-vinyl chloride (PVC) casings. A float system requires a large diameter casing with little or no deflection from vertical. The first model of submersible pressure transducer used had a short life span (generally 2 to 5 months) because of its susceptibility to moisture accumulation in the breather tube or in the electronics of the transducers.

The data-collection needs of the project required a sensitive and stable water-level sensor with a history of extended longevity in field installations. The sensor also needed to fit inside the 2-inch diameter piezometers, to be easy to install and maintain, and to be relatively inexpensive to procure. The Design Analysis WaterLog H-300 (H-300) was selected for data collection during this study because of the factory specifications for accuracy and stability (lack of calibration drift) and because it met the above requirements. At the onset of this study, the H-300 was considered by many investigators to be the state-of-the-art submersible transducer in its price range. Other benefits of the H-300 are its Serial to Digital Interface, 12 volt (SDI-12) output; its compatibility with the Campbell Scientific CR-10 data loggers, which were already being used for the study; and its relatively low power consumption. The H-300s have produced excellent results and are still being used in the study.

During the period of June through December 1992, H-300s were installed in 15 piezometers at 8 sites on EAFB. Fourteen of the 15 H-300s have an output range of 0 to 5 pounds per square inch (psi), which equates to a range of 0 to 11.53 feet. When the data logger is set to record at high resolution, a precision level of 0.001 psi can be recorded. The remaining H-300 has a 0- to 15-psi range, which equates to a range of 0 to 34.60 feet. Recording data at high resolution resulted in psi values that could be recorded to 0.003-psi precision. After converting the output to feet, a precision of 0.0023 foot for the 5-psi model and 0.0069 foot for the 15-psi model could be achieved. The 15-psi H-300 was installed in a

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piezometer that registered large daily and seasonal changes in water level due to the proximity of the piezometer to the major production well field. In addition to ground-water levels, aquifer-system compaction, barometric pressure, and rainfall also are being recorded at selected sites within the EAFB study area. All data are recorded to Pacific Standard Time.

Ground-water levels in the monitored piezometers ranged from about 20 to 150 feet below land surface. Seasonal water-level variations in individual piezometers ranged from as little as a few tenths of a foot to more than 20 feet. Five of the piezometer sites were near a primary production well field where the greatest amount of land subsidence on EAFB has been documented. During the pumping season, the water level in the deepest piezometer at the site closest to the production wells fluctuated daily by as much as 7 feet. This particular piezometer was instrumented with the 15-psi range H-300.

Several of the transducers had to be repositioned periodically due to seasonal water-level changes. In one instance, the transducer was subjected to more than twice its listed range of 5 psi with no apparent damage or change to its calibration. After repositioning, the transducer continued to perform well. In another piezometer, the water level dropped to less than 0.01 psi. The physical water-level measurement made at the time verified the H-300 output. Both of these examples demonstrate that the entire output range of the H-300 is extremely reliable.

Calibration of each transducer was done in the field at the time the transducer was installed in the piezometer and was checked each time a transducer was repositioned. Calibration was performed by moving the transducer in equal increments through the water column and then recording the transducer output and the corresponding distance that the transducer was moved. A minimum of four incremental calibration points that spanned the factory calibration range were used. The data pairs were used to compute a regression equation that would convert psi to the depth of the transducer below water surface. The equation was then combined with an offset based on the water level measured by a calibrated tape at the time the transducer was set in its final position. The final equation converts the transducer output, in psi, to water level as Depth Below Land Surface (DBLS), in feet.

The recorded psi values are not converted to DBLS in the data logger. These values are retrieved using a portable field computer and PFC software provided by the USGS Hydrologic Instrumentation Facility and are then transferred to the Automated Data Processing System (ADAPS) database on the California District Prime computer. All EAFB project data are stored and computed in ADAPS. After the data are loaded into the database, the equation for converting psi to DBLS is applied as a conversion of input rating. A copy of the conversion equation is kept in the instrument shelter so that the servicing hydrographer can determine a computed value of DBLS to compare with the physical measurement of DBLS.

There are several advantages to recording only psi with the data loggers rather than recording computed values of DBLS. Recording only psi, which consists of one or two numbers to the left of the decimal point, allows the best use of the high-resolution recording option of the CR-10 data logger. Another important advantage is the ability to determine when the H-300 is nearing the upper or lower limit of its range, which cannot be determined easily if DBLS is the recorded value, especially if a field person is not familiar with the instrumentation at each site. A third advantage involves quality assurance of the data. When coefficients and offsets are changed in the data logger, problems are more difficult to track. Data corrections are easier to track when the corrections are done only in the database, which is self-documenting.

Physical measurements of water levels are done using a calibrated steel tape or a calibrated electric tape. On each field run, duplicate measurements of DBLS are made with both types of measuring tapes. This duplication is done to determine if the electric tape readings are stable over time, or if the readings are drifting when compared with readings taken with a steel tape. A log book of the comparative measurements is kept for the record. Use of a calibrated electric tape is preferred for three reasons. First, it requires minimal submersion, thus minimizing the potential of the tape to disturb or to become entangled with the H-300. Second, it is easier to use than the steel tape when making the required duplicate water-level measurements. Third, it works well in wet weather when keeping a steel tape dry is difficult. Reliable water-level measurements cannot be obtained with a wet steel tape.

The stability of the H-300 calibrations varied. All but one transducer had a tendency to drift, as indicated by the increasing differences that were noted between the converted output of the transducers and the physical water-level measurements. The drift was always in one direction. A negative adjustment, which increased with time, was needed to correct the computed water levels to the measured water levels. The maximum adjustments needed ranged from 0 to -0.35 foot for the fourteen 5-psi models and -0.44 foot for the one 15-psi model. The above corrections were documented for data collected prior to October 1, 1993, and were applied during data processing in ADAPS.

In four cases, output of the transducer was examined by using linear regression techniques to help determine if the drift was a function of time, stage, or a combination of both. The strongest statistical correlation of the drift was to time. Because of this, only a time prorated correction was applied to data when computing the water levels in ADAPS. A possible explanation of drift over time is that there may have been drift in the temperature sensor of the H-300. Because the value for psi of a given volume of water is a function of the water density, and water density is a function of the water temperature, any drift in the temperature sensor will result in a drift in the psi value. Another explanation for drift over time could be fatigue of the pressure sensing diaphragm. In general, the transducers most affected by drift were in piezometers that had the most frequent and largest fluctuations in water levels. There also was indication of a hysteresis component to the drift, which, in one case, amounted to 0.04 foot. This hysteresis was associated with seasonal stage fluctuations. The stage-related hysteresis possibly could be the result of expansion and contraction of the stainless steel line from which the H-300 is hung or inaccuracies in the calibration procedure caused by the displacement of water in the 2-inch piezometer as the transducer was raised and lowered. In spite of the tendency to drift, the H-300s still performed well. The drift was documented easily and compensated for during the computational process.

Another unique feature of the H-300 is its dry-air system. Unlike most other submersible transducers, the breather tube of the H-300 is made of larger diameter poly-tubing, an improvement over the capillary tubing commonly used in transducers. Small moisture droplets cannot block the free passage of atmospheric pressure in large tubing as they can in small tubing. However, the use of larger diameter poly-tubing with the H-300s greatly increases the volume of air that must be dehumidified. The H-300 can be purchased with a dry-air system that has a large volume, but it might not be large enough to accommodate the volume of air in the breather tube. Even with the large dry-air system, frequent changes of the desiccants were needed. The longest lengths of tubing required even more frequent exchanges of the desiccants. Improving the quality of the desiccating material and increasing its volume could help to reduce the frequency of these exchanges.

Only two failures of the transducers were experienced and both were related to the accumulation of moisture on the electronics of the transducer. The only way that this could occur, other than a direct leak in the system, is for condensation in the tubing to settle into the transducer. The tubing must be supported by a suspension system that will not allow it to slip downward. This system is separate from the suspension system that is used to hang the transducer in place. Kinks in the poly-tubing have been caused by slippage, thus weakening the tubing where it is bent. This weakening of the tubing allows moisture to enter through micro-cracks. The poly-tubing also is slippery and difficult to fasten firmly. These problems can result in damage to the tubing from kinks, small cuts, and abrasions. This damage could allow atmospheric moisture to enter the system.

Overall, the H-300 is reliable and offers relatively trouble-free operation. During the period from June 1992 through September 1993, the EAFB study experienced only two failures out of the original 15 H-300s that were installed. Those two failures occurred approximately 12 and 14 months after installation. The H-300 has demonstrated a marked increase in life expectancy over the other submersible pressure transducer that was used during the study. It also has been proven to be extremely useful in narrow diameter installations where a float system cannot operate properly. The reliability and precision of the data collected are well suited for geohydrologic studies where the analysis of aquifer-system compaction and aquifer mechanics is a component.

Accuracy of Pressure Transducer Readings, 1991 to 1992, Black Swamp, Eastern Arkansas

By Gerard J. Gonthier[1]

Ground-water and surface-water levels were continuously recorded in Black Swamp, Arkansas, using HydroNET-300-5 pressure transducers. The Waterways Experiment Station, a branch of the U.S. Army Corps of Engineers, is conducting an extensive study of the Black Swamp bottomland hardwood wetland in eastern Arkansas. As part of the study, the U.S. Geological Survey is studying the ground-water flow system within the Black Swamp wetland to better understand:

(1) ground-water flow conditions, and
(2) ground-water surface-water interaction.

Water levels were measured in 119 wells and at 13 staff gages in and around the Black Swamp. Differences in ground- and surface-water levels were measured at locations within the wetland. These locations are well nests usually consisting of a 2-inch well completed just below the confining unit in the upper part of the alluvial aquifer (5 to 15 feet deep), a 2-inch well completed in the confining unit (2 to 6 feet deep), and a staff gage. Well openings were 2-inch PVC (polyvinyl chloride) casing with 0.02-inch wide horizontal slots. Sand was placed around the openings, and bentonite was placed around the casing from the top of the opening to the land surface. The bentonite is gelatinous when wet and clings to the well casing even if the well is bumped, effectively working as a seal to prevent leakage along the casing. All well and staff gage altitudes were surveyed to the nearest 0.01 foot.

Three HydroNET-300-5 pressure transducers were installed in each of two well nests. The pressure transducers are submersible with a vented cable that terminates at a small junction box which has an air hole that allows atmospheric pressure changes to reach the gage port of the transducer. Pressure range is 0 to 5 pounds per square inch or 0 to 11.53 feet. Manufacturer's specification for transducer accuracy is "less than or equal to 0.02 percent (± 0.002) over a temperature range of -5 to 50 [degrees Celsius] (non-freezing) referenced to a straight line stretched from 0 to 5 [pounds per square inch]". Pressure transducer output is SDI-12.

At each of the two well nests, a 10-foot high platform was built next to the two wells and staff gage. A metal water-proof box was mounted at the top of the platform and a 2-inch stilling well was mounted on the side of the platform. The water-proof box housed the battery, Campbell Scientific electronic basic data recorder 301, and the pressure-transducer junction boxes. The stilling well had 2 feet of screen just above the land surface and 8 feet of casing above the screen. The stilling well minimized surface-water wave action and protected the transducer during flooding. The data recorder was programmed to initiatemeasurements at set intervals, which ranged from 30 minutes to 3 hours, and to record output of water levels in feet using 2.307 as the multiplier.

Both well-nest installations were insufficiently grounded. A copper rod was hammered about 2 feet into the ground, and a copper wire connected the rod to the housing box. Ground wires from the pressure transducers and the data recorder were connected

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to each other, but not to the housing box. Thus, the transducers were not connected to earth ground.

The pressure transducers were installed from March 21, 1991, to August 9, 1991, and November 25, 1991, to October 9, 1992. Solar panels and voltage regulators were added near the end of the first period to keep the batteries charged. The gap in the data was due to a request by the distributor to return the transducers for an "upgrade."

Pressure transducers have aided in the study of ground and surface water in a wetland. Sudden rises in shallow ground-water levels were detected during rainfall. These water- level rises can be used to better understand the hydraulic properties of the confining unit and the upper part of the alluvial aquifer. Diurnal fluctuations of as much as 0.38 foot occurred during the growing season and are attributed to evapotranspiration. During rising surface-water levels, flow is from the surface, through the confining unit, and into the upper part of the alluvial aquifer. During falling surface-water levels, flow is from the upper part of the alluvial aquifer, through the confining unit, and to the land surface.

Power-supply or moisture problems appear to have caused fluctuations in output. Erratic readings occurred when moisture levels became very high. Diurnal fluctuations of about 0.05 foot in ground-water levels were apparent during the winter months, and had a distinctly different pattern from those that occurred during the growing season. Unnatural fluctuations that were apparently not attributable to power-source or moisture problems also occurred and were analyzed to calculate the accuracy of readings from insufficiently grounded pressure transducers used in this study.

The two well nests were visited to obtain accurate water-level measurements in order to calibrate pressure-transducer readings. Steel tape and staff gage readings usually were done before and after data were downloaded. Calibration checks were done during site visits, which average every 14 days before the upgrade and every 18 days after the upgrade with a maximum range of visitation period of 4 days to 1 month. Ground-water-level checks were done with a steel tape; surface-water checks were done by reading the staff gage.

The word "drift" is used here to describe the change in difference pressure-transducer output (offset) from one site visit to the next. Offset plus the pressure-transducer reading equals the steel tape or staff gage measurement (assumed to be the true water level). Thus,

$$\text{Drift} = (P_2 - S_2) - (P_1 - S_1)$$

where P is the pressure-transducer reading, S is the true water level, (P - S) is the pressure-transducer offset, and the subscripts 1 and 2 are times of two consecutive site visits, respectively. Absolute values of drift are statistically analyzed in order to describe the accuracy of pressure-transducer readings compared to true-water levels. The smaller the absolute values of drift, the more accurate the pressure-transducer readings.

A histogram of 133 calibrations made for readings from all 6 pressure transducers (fig. 5) shows that 75 percent of the pressure-transducer readings drifted less than 0.07 foot from the actual water levels based on the field checks. Ninety-five percent of the pressure-transducer readings drifted less than 0.2 foot, 4 percent of the readings drifted about 0.5 foot or more, and 1 percent of the readings drifted 1.80 feet. Field quality assurance and control measures were taken to rule out human error during field checks. The median, third quartile, and mean of the absolute values of drift and half of the interquartile range of the drift (table 1) indicate that pressure-transducer readings were less accurate after the upgrade than before the upgrade. A rank-sum test comparing readings before and after the upgrade confirm the decrease in accuracy with a p-value of 0.0019. The decrease in accuracy after the upgrade may be due to an increase in sensitivity to improper grounding and not necessarily be due to a failure by the manufacturer. There was no correlation between drift or absolute value of drift and the time or change in water level between site visits.

Drift in pressure-transducer readings has restricted the interpretation of continuous-recorder data. The minimum desired accuracy is about 0.02 foot. Based on the third quartile values, accuracy is about 0.07 foot or about 3 1/2 times the minimum desired accuracy. Insufficient grounding is suspected to be the cause for the inaccuracy in these pressure transducers. Another project being conducted by the U.S. Geological Survey in Arkansas, sometimes using the same transducers used in the wetland, had proper grounding and had drift of less than 0.02 foot. Despite problems with accuracy due to the insufficient grounding, pressure-transducers have collected valuable data concerning ground-water flow in a wetland.

Table 1. Statistical summary of changes in pressure transducer readings with respect to true water levels, Black Swamp, eastern Arkansas [Drift, the change in pressure-transducer offset between two calibration measurements; N, sample size; Q_3, the 75 percentile (third quartile); IQR/2, half of the interquartile range]

Data collection period	Statistical parameters							
	Absolute value of drift (in feet)				Drift (in feet)			
	N	Median	Q_3	Mean	Median	IQR/2	Mean	Standard deviation
March 1991 to August 1991	52	0.02	0.05	0.07	0.01	.020	-0.02	0.255
November 1991 to October 1992	81	.04	.08	.10	.00	.045	-.02	.245
Total	133	.03	.07	.09	.00	.035	-.02	.248

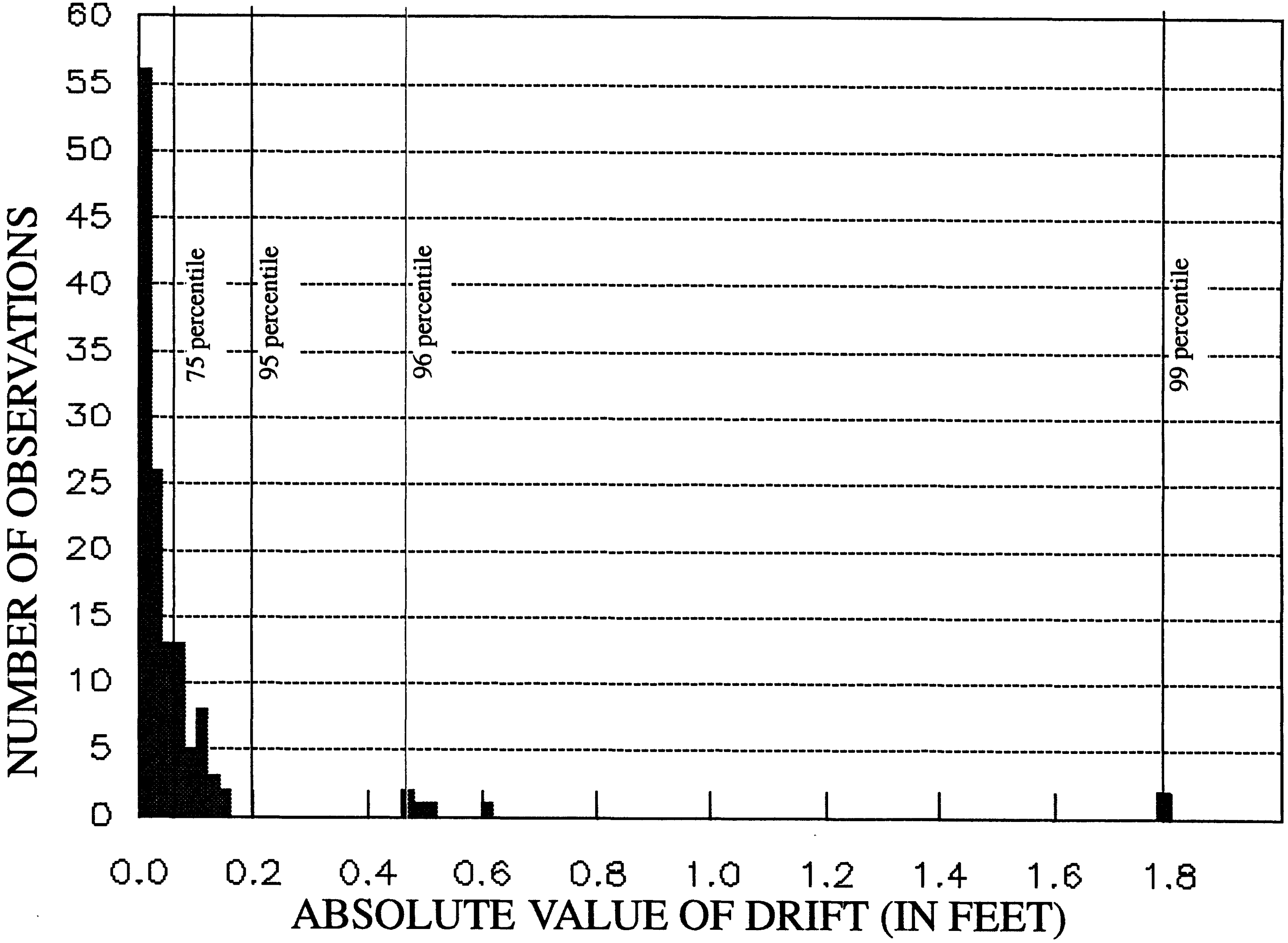

Figure 5. Distribution of the absolute value of drift in pressure transducer readings with respect to true water levels, 1991 to 1992, Black Swamp, eastern Arkansas.

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Monitoring of Specific Conductance And Ground-water Level Fluctuations in a Municipal Wellfield, Pinellas County, Florida.

By Raymond A. Mularoni[1]

The Eldridge-Wilde well field, located in Pinellas County along the west-central coast of peninsular Florida, produces about 30 million gallons of water a day from the Upper Floridan aquifer. The County is currently running borehole geophysical logs of fluid conductivity in about 30 wells within the wellfield to assess the effects of pumping on saltwater intrusion. As a substitute for geophysical logging, continuous monitors were installed in salt-water interface monitor well 1D to obtain records of water levels and specific conductance of water in the Upper Floridan aquifer.

Salt-Water Interface Monitor well 1D is located near the southwestern boundary of the wellfield. The well was drilled to locate and monitor movement of the saltwater-freshwater interface. The well is 800 feet deep and contains 580 feet of 4-inch casing. Samples taken with the geophysical logger confirm a saltwater-freshwater transition zone between 590 and 770 feet below land surface. This experimental well required a sensitive and stable specific conductance monitoring device and a pressure transducer adapted for the small diameter borehole. The instrumentation selected for this site consisted of a Campbell CR-10[2] data logger, a U.S. Geological Survey water quality mini-monitor, and a Transmetrics Model P-21[2] strain gage pressure transducer. Specific conductance of water at the well site ranges between 1,200-1,800 microsiemens per centimeter at 25 degrees Celsius; the mini-monitor was calibrated prior to installation using standards of 1,000 and 2,530 microsiemens. The specific conductance probe was set to an inital depth of 730 feet below land surface in the lower part of the transition zone. Water-level fluctuations were expected to range between 5 and 15 feet. The pressure transducer was set to a depth of 25 feet below land surface and was calibrated on site using simple linear regression techniques. Continuous hourly measurements of specific conductance and water level were collected from July 1993 through January 1994 and stored in the Automated Data Processing System (ADAPS).

Calibration of the mini-monitor was checked at the time of removal using standards of 1,010 and 2,470 microsiemens. The percent of error or drift was within five per cent of the standards values after seven months of operation. Water-level measurements were collected bi-weekly with a steel tape. A comparison of pressure transducer readings with steel tape measurements indicated that drift occurred and ranged from -0.05 to -1.35 feet. Data provided by the Transmetrics Model P-21 is considered unreliable and was not acceptable for this application.

Pressure transducer drift can be attributed to several factors. First, the transducer was purchased in 1989 and was built without a venting tube that would link it with the atmosphere. Changes in atmospheric pressure, therefore, may have contributed to measurement error. Second, the transducer was suspended in the well casing by its shielded cable which was susceptible to possible slippage from its attach point. Third, cable expansion/contraction from temperature changes also may have contributed to error.

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[2] Mention of a brand name is for description purposes only and does not constitute endorsement of products.

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Possible Designs and Installation of Submersible Pressure Transducers for Use During Floods

By Nathan C. Myers[1]

INTRODUCTION

In July 1993 extreme high-water conditions were experienced at stream-gage sites near the Junction City and Manhattan, Kansas, well fields, where submersible pressure transducers were being used to measure stream stage. The high water provided an opportunity to consider transducer and transducer-installation designs. This paper presents those ideas about designs -- some of which have been tried, some have not.

The discussion in this paper is applicable to the Design Analysis model H-300[2] (H-300) submersible pressure transducer but generally could be applied to any similar transducer. These pressure transducers sense water pressure and water temperature and are compatible with the Sutron model 8200 data logger. Each transducer's pressure value is converted to depth by the data logger using a pressure-to-depth conversion factor. The transducer is connected to the data logger by a three-wire cable that runs through a vent tube. The purpose of the vent tube is to compensate for the effect of changes in atmospheric pressure on the water pressure sensed by the transducer. The data-logger end of the vent tube must remain dry to prevent moisture from traveling down the vent tube and into the transducer's electronic components.

PURPOSE

This paper presents several ways to improve the utility of pressure transducers and simplify their installation by design changes to the transducer and to the gage and orifice-pipe installation.

ADVANTAGES AND DISADVANTAGES OF USING SUBMERSIBLE PRESSURE TRANSDUCER

Using a submersible pressure transducer to measure stream stage has advantages over gas-purge systems, but it also has disadvantages. Advantages include:

- Operation without a nitrogen tank and gas-purge system
- Simple three-wire hook-up in the gage house
- Transducer can be installed in a 1.5-inch diameter or larger orifice pipe
- Transducer gives accurate readings when buried in streambed sediment in that it eliminates pressure build-ups and releases characteristic of buried gas-purge system orifices

The disadvantages of using a pressure transducer to measure stream stage include:

- Floodwater can enter the gage house and the transducer vent tubing and damage the electronics
- Transducer must be protected from freezing
- Vent-tubing length is not easily adjustable
- Transducer is vulnerable to debris and strong currents that could damage the orifice pipe
- Transducer is difficult to secure inside the end of the orifice pipe

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[2] The use of brand names in this paper is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey

TRANSDUCER DESIGN

Transducer requirements vary depending on the goals and data-collection needs of hydrologic studies. Some studies may need transducers to measure ground-water levels, whereas other studies may need transducers to measure stream stage. The optimum design would be a single instrument that could be adapted for many uses. This could be accomplished through design changes or additions to submersible pressure transducers to make them waterproof during floods, resistant to freeze damage, and to have easily adjustable vent tubing.

To prevent atmospheric moisture from reaching the transducer, the manufacturer of the H-300 provides a dry-air bottle and desiccant packs to isolate the vent tube and transducer from direct atmospheric contact. This arrangement, however, is not adequate to prevent transducer damage during complete submergence. During July 1993, floodwater overtopped the gage house at Manhattan, Kansas, filled the H-300's dry-air bottle, and flowed down the vent tube into the transducer. This resulted in transducer damage, deinstallation and reinstallation costs, manufacturer repair costs, and lost data because of the downtime.

To prevent water from entering the dry-air bottle and vent tube, a float valve could be designed to seal off the bottle and vent tube in the event of high water. An alternative would be to extend a snorkel from the dry-air bottle up to a height above the gage house. The electronics box on top of the dry-air bottle also should be completely sealed from water.

At the Junction City, Kansas, site, the July 1993 flooding scoured and deepened the river channel. As a result, during low streamflows in February 1994, the pressure transducer was exposed to air and freezing nighttime temperatures. The residual water in the transducer froze, damaging the pressure-sensing diaphragm. Pressure readings from the transducer after the freeze were very erratic and unreliable. In addition to the cost of transducer repair, there were deinstallation and reinstallation costs, and lost data due to the downtime.

To prevent freezing, an elastic bladder, filled with an antifreeze fluid, could be fitted over the end of the transducer and sealed to the transducer shank. This system probably would need a pressure-relief valve on the bladder in the event that the transducer became entirely encased in ice. This could create pressure that exceeds the transducer design capacity.

Submersible pressure transducers would be more adaptable to various applications if the vent tubing came in standard lengths, with industry-standard connectors that could be combined to form custom-length tubes. To use the transducer in a well, the vent-tubing length only needs to reach the shelter on top of the well. Three-wire shielded cable then can be installed from the well shelter to the data-collection instrument. To use the transducer in surface-water installations, however, the transducer vent tube and wires must be threaded through a 1.5-inch diameter or larger orifice pipe from the stream to the gage house and may be 100 to 500 feet long. Being able to customize the length of the vent tube would make installation easier and less expensive. In addition, if the vent tubing could be easily disconnected from the transducer, installation of the transducer in an orifice pipe would be easier. Without a disconnect, the vent tubing must be pulled back uphill from the orifice-pipe end to the gage house.

TRANSDUCER-INSTALLATION DESIGN

Currently, there are no "off-the-shelf" hardware items for installing transducers in an orifice pipe. Two conditions need to be met to secure the transducer and to ensure quality data--a secure orifice pipe and a secure transducer in the orifice pipe.

A secure orifice-pipe installation protects the transducer from the hazards of moving debris and strong currents. The orifice pipe should be clamped to steel posts or in some other way attached to the riverbank to prevent movement. Debris that collects on the orifice pipe should be removed to lessen current stress on the orifice pipe. The transducer should be inside the orifice pipe--not exposed directly to the river environment.

The transducer must be secured in the end of the orifice pipe to keep it from shifting and to keep pressure readings accurate. If transducers were equipped with threaded bodies or couplings, it would be a simple procedure to install the transducer in the end of an orifice pipe. Other possible options to install transducers include: (1) Apply construction foam in the annular space between the transducer and the inside of the orifice pipe. A custom-fit plug could be slipped around the transducer and into the orifice pipe to keep the transducer centered in the pipe and to keep the foam from obstructing the transducer pressure ports. This method would be somewhat messy and, although easy to install, would not be as easy to remove. If a closed-cell foam were used, there may be an added advantage because water could not enter the inside of the orifice pipe. This could prevent freezing water from pinching off the transducer vent tube. (2) Silicone caulk could be used to secure the transducer in a threaded pipe or coupling with an inside diameter slightly larger than the transducer. The pipe or coupling then could be threaded into the orifice pipe using reducers or adapters as needed. This design would be easy to install and easier to remove than the construction-foam installation. (3) The transducer could be secured in a pipe fitting that is threaded inside and out, with a flange on the inside to accommodate a compression fitting. The transducer then could be inserted and secured in the pipe by tightening the compression fitting. This design would be simple to install or remove but would require a special pipe fitting.

CONCLUSION

Design changes or additions to submersible pressure transducers to make them waterproof during floods, resistant to freeze damage, and to have easily adjustable vent tubing would help overcome some of the disadvantages of using pressure transducers to measure stream stage. Design changes to orifice-pipe installations would ensure that the transducer is secure in the orifice pipe, gives accurate readings, and is protected from damage by strong currents or floating debris.

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Equipment and Procedures for Monitoring Deep Water Levels at Yucca Mountain, Nevada

By Grady M. O'Brien[1]

Submersible pressure transducers have been used to monitor water levels in 19 wells completed in 29 depth intervals in the Yucca Mountain area, Nevada since 1985. Depth to water in these wells ranges from 900 to 2,500 feet, and averages 1,625 feet. Transducer output are recorded by data loggers and data collection platforms (DCP) at the land surface. Daily and earthquake-induced water-level fluctuations have been monitored to aid in the characterization of Yucca Mountain, a potential site of the nation's first high-level nuclear-waste geologic repository.

Several brands of pressure transducers were used in the early years of saturated-zone investigations; however, transducers manufactured by Druck, Inc[2]. have been used almost exclusively by the project since 1988. Exclusive use of Druck transducers occurred primarily because of the desire to obtain consistency in the equipment used throughout the water-level monitoring network. Absolute and gage-pressure transducers with voltage excitation and output were used from 1985 to 1992; however, gage-pressure transducers with current excitation and output have been used exclusively since 1992. Gage-pressure transducers, which use atmospheric pressure as a reference, are preferred to absolute-pressure transducers. Less data processing is required to convert gage-pressure transducer output to water levels because gage-pressure measures only pressure changes associated with water-level fluctuations. Most wells in the area have barometric efficiencies near 100 percent and output from absolute transducers was nearly constant. When an increase in barometric pressure caused a decrease in water level, the absolute-pressure transducer sensed the increase in barometric pressure as well as the decrease in pressure related to the decrease in water level. The pressure changes were nearly equal and opposite in sign, therefore, the transducer output did not change and was not representative of the actual water-level fluctuations. The performance of the absolute-pressure transducers was difficult to assess and further data processing was required to remove the effect of barometric pressure.

Current-mode transducers are preferred to voltage-mode transducers because they have more stable output signals. Voltage signals have inherent problems when used with long lead lengths, which are required to reach the water surface at Yucca Mountain. Resistance in the cable and signal instability due to weather conditions are significant problems. A current signal is not significantly affected by changes in resistance or weather conditions. Advantages of current-mode transducers include a cleaner signal requiring less processing and an increase in the amount of useable data. Useable transducer data increased by 30 percent from 1985 to 1992 (figure 6). Because the data loggers cannot measure current, the transducer output signal is measured as a voltage drop across a resistor.

Daily water-level fluctuations in the Yucca Mountain area are generally less than 0.5 feet in amplitude. In order to accurately measure fluctuations of this magnitude, trans-

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[2] Use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

ducers with 1, 2.5, 5, and 10 pounds per square inch (psi) pressures have been used. The most commonly used pressure for routine monitoring has been 5 psi. In wells equipped to monitor fluctuations caused by seismic activity, 20 psi transducers have been used so a larger range of water-level fluctuations could be measured.

Transducer reliability has been a concern regardless of the type of transducer. From 1990 to 1994, 52 current-mode transducers were installed in wells to measure water-level fluctuations. The average length of service was 361 days and the range of service was 14 to 1,211 days. Of the transducers used during this period, 55 percent were in service for less than one year. No definitive cause for the failures has been determined. However, because gage-pressure transducers have vent tubes terminated 30 feet above the water surface in a nearly 100 percent humidity environment, moisture may be reaching the electronics in the transducer body and affecting the transducer performance. However, all transducers are subjected to similar operating environments, and given the wide range in length of service for the transducers, moisture in the transducer body cannot be solely responsible for the failures. The effect of impact shock on the transducers has not been quantitatively addressed, but it may also play a role in transducer failure. For example, when a transducer, which has been functioning properly, is raised and lowered in a deep well, the chance of failure increases. The transducer may be damaged from contact with the casing when it is installed and removed from the well.

Transducer output has been measured and stored by Handar 570A DCP's and Campbell Scientific 21X microloggers. All wells have been equipped with data collection platforms and current-mode gage-pressure transducer systems since 1992. Data collection platforms transmit data to satellites that relay the data to ground stations and project computers allowing near real-time monitoring. Data processing and access is simplified because the data are input directly into the Automated Data Processing System (ADAPS), a sub-system of the National Water Information System data base. Daily access to transducer output is a valuable tool in assessing performance of the data collection system and has decreased the amount of time between transducer failure and replacement. The increase in amount of convertible data is directly related to the decrease in time required to replace failed transducers (figure 6).

Applications that require more powerful programming capabilities than available with a DCP have utilized the 21X data logger. For example, seismic activity causes high-frequency water-level fluctuations that require multiple samples per second to adequately define the fluctuations. The 21X can be programmed to rapidly measure transducer output and only store data when there is a significant change in water levels. Digital data obtained from the 21X are useful for defining individual fluctuations, but may not record an entire event because sampling is initiated and ended by predetermined limits within the program. Analog chart recorders have been used in conjunction with 21X's to continuously monitor water-level fluctuations in the event of seismic activity. The chart recorders will contain the entire duration of the event because the recorder is continuously recording. Use of this secondary system increases the possibility of successfully recording the aberrant fluctuations.

Transducers are calibrated, in-situ, at the time of installation, at least every 4 months while in service, and if possible, at the time of removal. The transducer is lowered to the bottom of the calibrated interval and raised to specific points at which the output is recorded. Data loggers, chart recorders, and transducers are calibrated as a system. A unique calibration factor is determined for each monitoring system. The calibration factor relates the transducer output to depth of submergence. Water-level altitudes are calculated from depth of submergence data and depth-to-water measurements, made with calibrated steel tapes or multiconductor cable.

The use of gage-pressure current-mode transducers and DCP's has proven to be an effective method of routinely measuring water levels in the Yucca Mountain area. The use of this system has increased the amount of useable data, despite continuing problems with transducer failure.

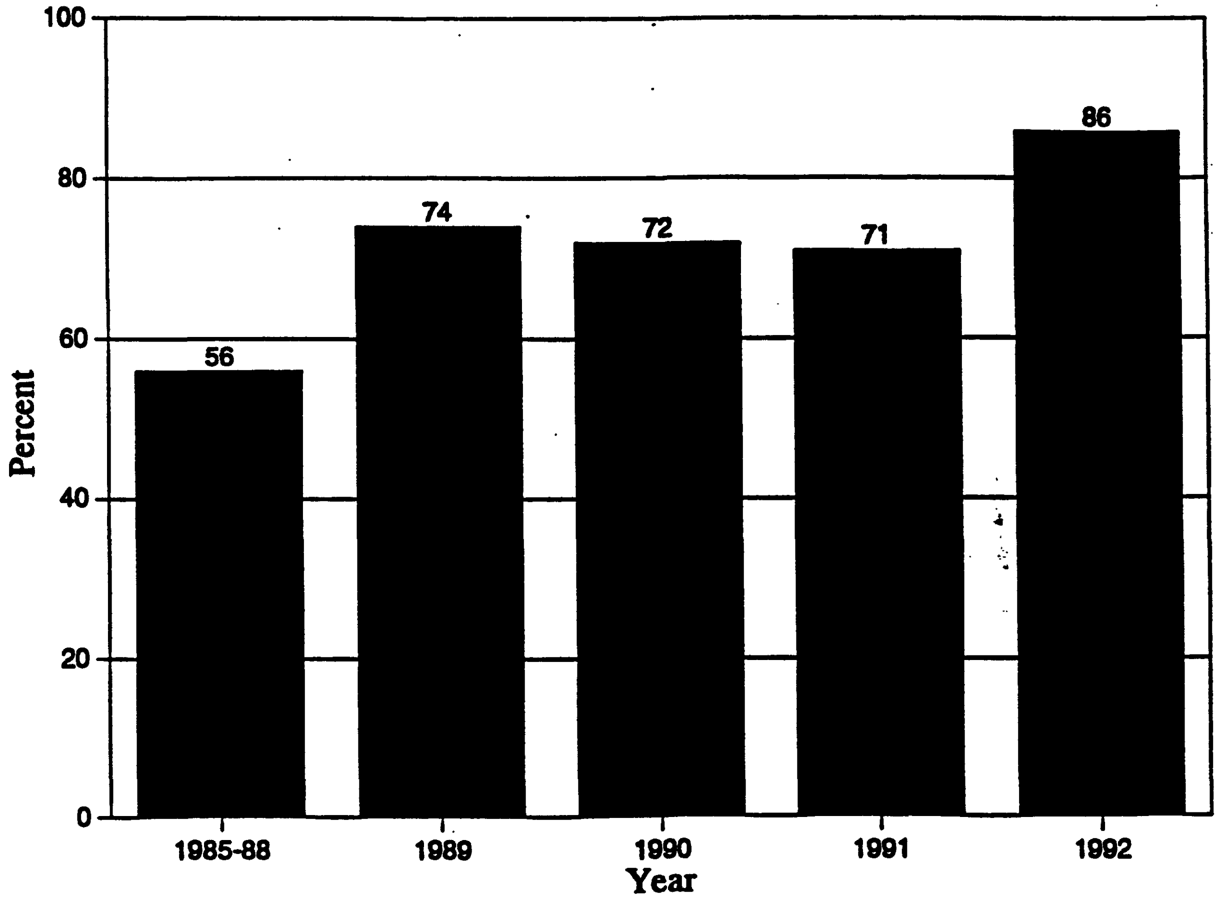

Figure 6. Percent of transducer data converted to water-level altitude, 1985-1992.

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Problems Associated with H-300-30 Pressure Transducer

By Keith Overton[1]

The HydroNet Pressure Transducer, H-300-30, can be a useful tool for monitoring ground-water fluctuations. However, in a study conducted by the U.S. Geological Survey to monitor ground-water fluctuations and possible recharge of the Kingshill aquifer on St. Croix, U.S. Virgin Islands, a problem arose with the transducer measurements. Some transducer measurements drifted over a range of more than ±0.50 foot on a weekly basis when compared to water-level measurements made with a steel tape.

For the recharge study, a series of dams were placed in three intermittent streams that transverse the Kingshill aquifer, so that ponds would form upstream of the dams, allowing the water to infiltrate and recharge the aquifer. Eight 6-inch wells were drilled on a line perpendicular to the stream at two locations within a 300-foot reach of the stream prior to dam construction. An H-300-30 transducer was installed at each well to measure the water level, and the data generated by the transducers were transferred to a Sutron 8200 Data Collection Platform (DCP), which then transmitted the data by way of a satellite to a Direct Readout Ground Station (DRGS). The data were then downloaded into the Prime computer. No malfunctions were detected in the DCP's operation during the study. The transducers were placed about 40 feet below the water surface in the well, and the water-surface elevation was recorded by the DCP at hourly intervals. To verify the accuracy of the transducers, the water level in each well was measured weekly with a weighted steel tape. The water level in the wells was monitored for about 14 months, prior to the installation of the dams, to determine the long-term trend in water-level change.

Water-surface elevations determined from field readings of the transducers were usually different than the water-surface elevation determined by tape measurements (figs. 7 and 8). Some of the transducer measurements differed from tape measurements by only ±0.02 foot, but most differences were larger and a few transducer measurements differed from tape measurements by more than ±0.50 foot (table 1). An analysis of the drifting problems associated with the use of the H-300-30 was beyond the scope of this study; however, the problems detected might have been caused by a variety of factors. These factors are discussed below.

1. **Moisture.** The H-300-30's were equipped with Dry Air Systems (DAS) designed to prevent moisture from degrading the electronics. The DAS desiccant bags were changed frequently, but the humidity ranged from 70 to 100 percent, and it is possible that the DAS was not adequate to prevent moisture damage.

2. **Heat.** The wellheads were vented, but the outside temperature rarely dropped below 75 degrees Fahrenheit and was usually between 85 and 98 degrees Fahrenheit.

3. **Design.** The early (1990-91) transducers might not have been designed to an environment as hot and humid as that in the study area.

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4. **Ground-water fluctuations.** The aquifer was stressed frequently by pumping from an established well field. Water-level fluctuations might have been too rapid for the transducer to sense accurately.

5. **Water quality.** High specific conductance measurements (4,000 microsiemens per centimeter) and chloride concentrations (300-1,100 milligrams per liter) in water in some of the wells could have affected the accuracy of the transducer measurements. However, fluctuations in chloride concentration and specific conductance within the water column in any individual well generally were less than 30 percent.

6. **Grounding.** The stations were grounded but were never checked with an earth ground resistance meter or any other instrument. Ineffective grounding could have caused the data drift.

At the present time (March 1994), further testing is being conducted to determine the cause of the drift. One of the transducers used during the study is being tested by the Miami Subdistrict of the U.S. Geological Survey. This transducer was placed in a well similar in construction to the wells on St. Croix and equipped with an Analog to Digital Recorder and float to verify the accuracy of the H-300-30. The depth of the test well in Miami is about the same as that on St. Croix (100 feet), the temperature and humidity are similar to those on St. Croix during most of the year, and the methods of retrieving data at the test site were the same as those used on St. Croix. The water level in the test well is also affected by nearby pumping. For this test, the transducer was modified in the factory from a 30- to 5-pound per square inch sensor, and the transducer was placed about 10 feet below the water surface to accommodate the new sensor and the conditions of southern Florida. Grounding was also improved and checked. Results of the tests are expected to be available in the summer of 1994.

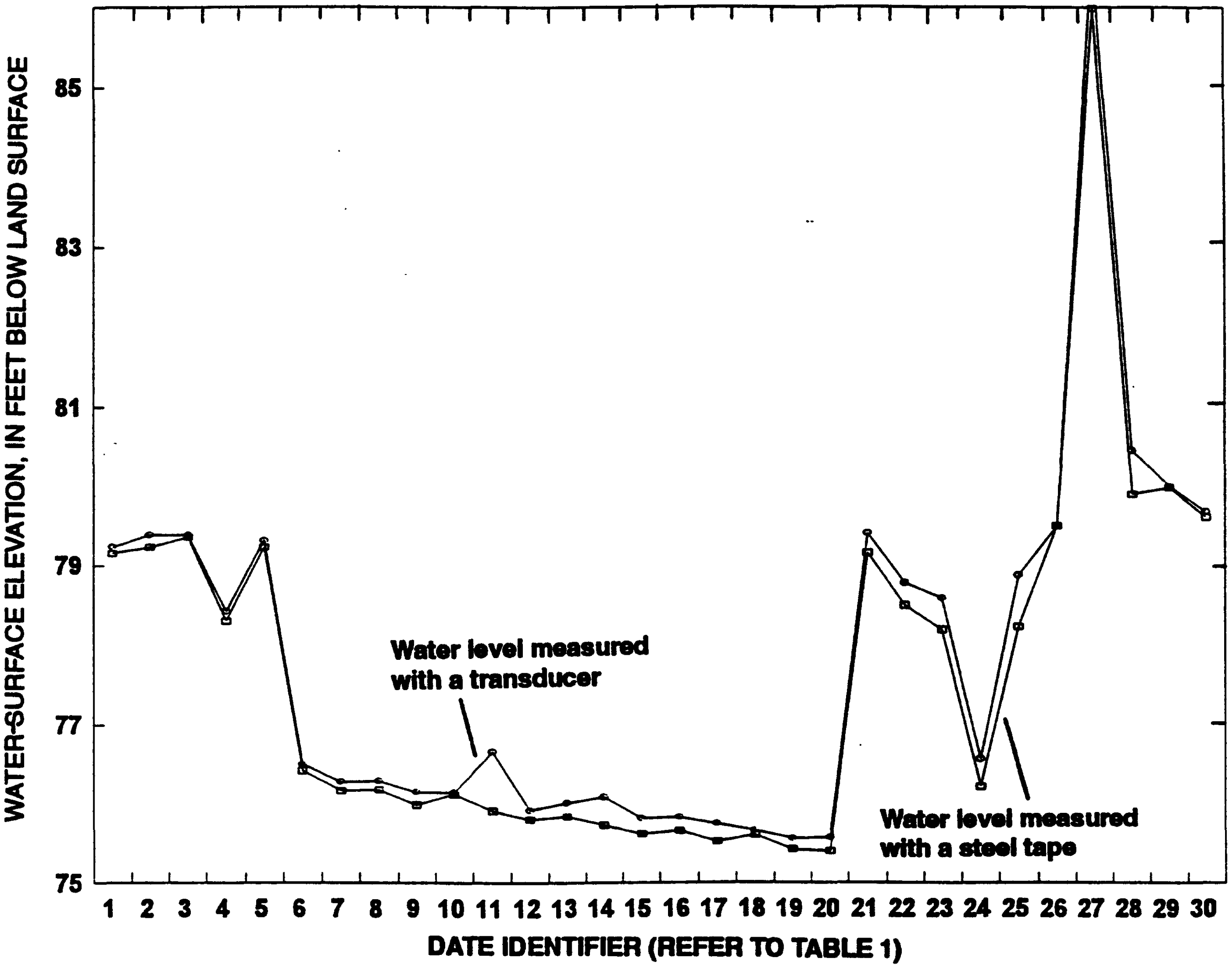

Figure 7. Transducer and tape-down water-level measurements for Fairplains well No. 4, 1992 water year.

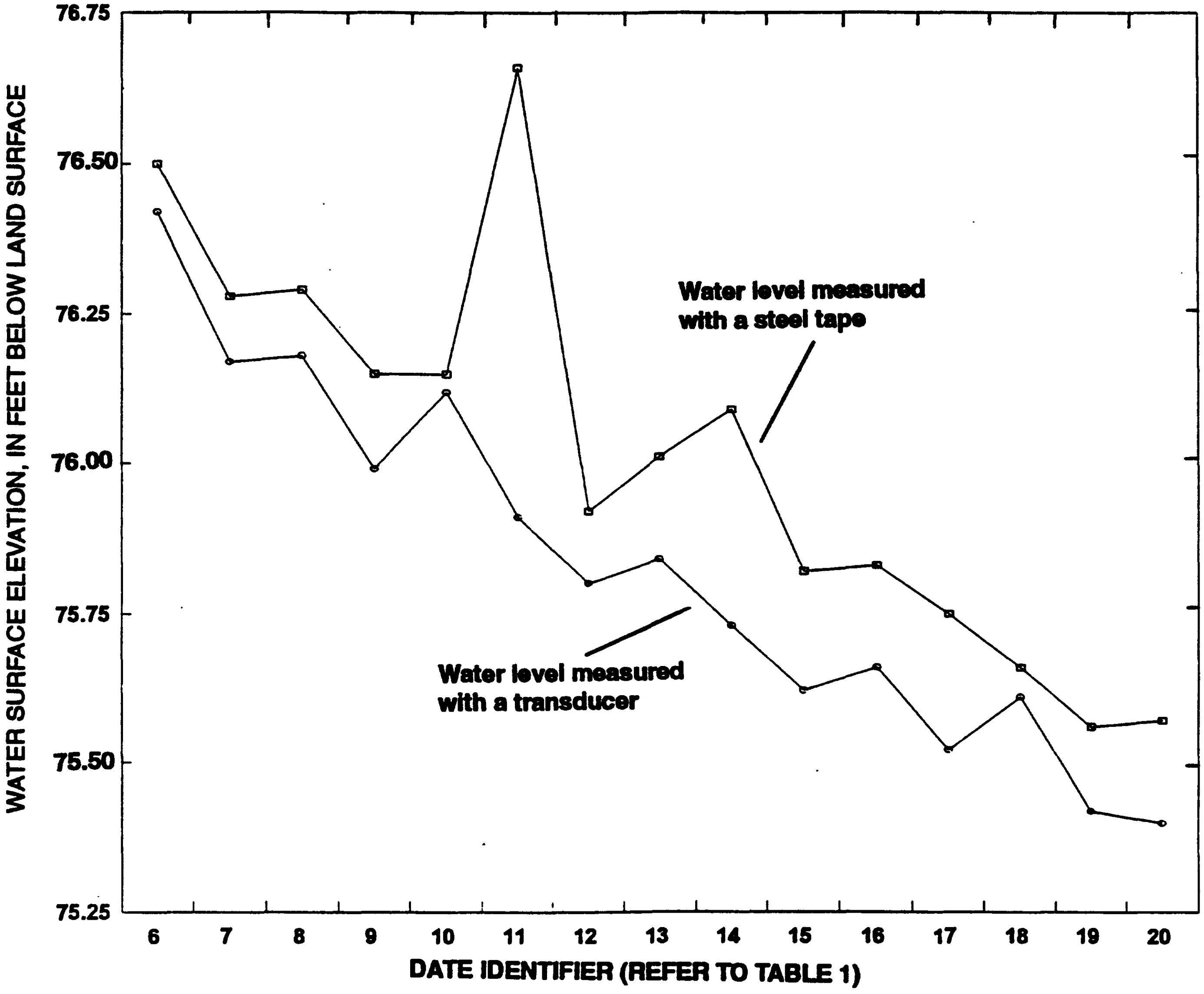

Figure 8. Transducer and tape-down water-level measurements for Fairplains Well No. 4, November 8, 1991, to February 14, 1992.

Table 2. Transducer drift observed in water-level measurements at eight wells at Fairplains, St. Croix, U.S. Virgin Islands, October 1991 through July 1992 [All water-level measurements are in feet bleow land surface; tape measurement made with steel tape; XDucer measurement made with transducer]

Identifier (refers to figs. 1 and 2)	Date	Water level in well 1			Water level in well 2			Water level in well 3			Water level in well 4			Water level in well 5			Water level in well 6			Water level in well 7			Water level in well 8		
		Tape	XDucer	Drift	Tape	XDucer	Drift	Tape	XDucer	Drift	Tape	XDucer	Drift	Tape	XDucer	Drift	Tape	XDucer	Drift	Tape	XDucer	Drift	Tape	XDucer	Drift
1	10-04-91	79.28	78.45	0.83	79.17	78.18	0.99	79.20	78.63	0.57	79.23	79.15	0.08	79.71	79.49	0.22	79.79	79.82	-0.03	80.22	79.71	0.51	80.01	79.90	0.11
2	10-11-91	79.43	78.51	.92	79.94	78.29	1.65	79.36	78.78	.58	79.39	79.23	.16	79.85	79.59	.26	79.91	79.92	-.01	80.36	79.82	.54	80.11	80.11	.00
3	10-18-91	79.43	79.41	.02	79.32	79.95	-.63	79.35	79.29	.06	79.39	79.36	.03	79.85	79.83	.02	79.92	79.91	.01	80.42	80.35	.07	80.16	80.08	.08
4	10-25-91	78.45	78.31	.14	78.35	79.95	-1.60	78.35	78.35	.00	78.42	78.30	.12	79.19	79.19	.00	79.31	79.29	.02	80.17	80.12	.05	79.66	79.64	.02
5	11-01-91	79.36	79.28	.08	79.26	79.87	-.61	79.28	79.16	.12	79.32	79.23	.09	79.80	79.74	.06	79.88	79.84	.04	80.36	80.29	.07	80.11	80.06	.05
6	11-08-91	76.72	76.62	.10	76.42	77.07	-.65	76.44	76.34	.10	76.50	76.42	.08	78.17	78.14	.03	78.38	78.31	.07	79.47	79.43	.04	78.79	78.78	.01
7	11-15-91	76.48	76.43	.05	76.17	76.17	.00	76.22	76.07	.15	76.28	76.17	.11	77.99	77.95	.04	78.21	78.17	.04	79.35	79.24	.11	78.65	78.61	.04
8	11-22-91	76.51	76.49	.02	76.19	76.21	-.02	76.23	76.10	.13	76.29	76.18	.11	77.97	77.90	.07	78.17	78.13	.04	79.25	79.11	.14	78.59	78.59	.00
9	12-02-91	76.36	76.27	.09	76.04	76.03	.01	76.08	75.85	.23	76.15	75.99	.16	77.83	77.76	.07	78.04	78.01	.03	79.30	79.14	.16	78.49	78.49	.00
10	12-05-91	76.37	76.38	-.01	76.04	76.06	-.02	76.09	75.98	.11	76.15	76.12	.03	77.78	77.72	.06	78.01	77.98	.03	79.23	79.06	.17	78.46	78.57	-.11
11	12-13-91	76.51	76.20	.31	76.30	77.52	-1.22	76.45	75.77	.68	76.66	75.91	.75	78.12	78.70	-.58	79.03	79.66	-.63	79.13	79.04	.09	79.77	79.68	.09
12	12-20-91	76.16	76.18	-.02	75.82	75.87	-.05	75.87	75.67	.20	75.92	75.80	.12	77.59	77.55	.04	77.81	77.73	.08	78.87	78.67	.20	78.21	78.24	-.03
13	12-27-91	76.26	76.28	-.02	75.91	75.96	-.05	75.95	75.77	.18	76.01	75.84	.17	77.67	77.70	-.03	77.86	77.76	.10	78.76	78.55	.21	78.24	78.26	-.02
14	01-03-92	76.36	76.16	.20	76.02	75.99	.03	76.04	76.71	-.67	76.09	75.73	.36	77.68	77.66	.02	77.89	77.64	.25	78.66	78.40	.26	78.23	78.15	.08
15	01-10-92	76.06	76.00	.06	75.69	75.78	-.09	75.76	75.58	.18	75.82	75.62	.20	77.49	77.48	.01	77.68	77.57	.11	78.62	78.39	.23	78.07	78.11	-.04
16	01-17-92	76.07	76.00	.07	75.74	75.78	-.04	75.77	75.55	.22	75.83	75.66	.17	77.46	77.43	.03	77.60	77.53	.07	78.59	78.33	.26	78.04	78.06	-.02
17	01-24-92	75.97	75.87	.10	75.61	75.69	-.08	75.68	75.44	.24	75.75	75.52	.23	77.34	77.33	.01	77.52	77.52	.00	78.38	78.10	.28	77.86	77.95	-.09
18	01-31-92	75.92	75.93	-.01	75.57	75.49	.08	75.61	75.53	.08	75.66	75.61	.05	77.31	77.49	-.18	77.51	77.71	-.20	78.32	78.30	.02	77.87	78.03	-.16
19	02-07-92	75.82	75.82	.00	75.47	75.35	.12	75.51	75.21	.30	75.56	75.42	.14	77.21	77.35	-.14	77.42	77.60	-.18	78.18	78.15	.03	77.77	77.93	-.16
20	02-14-92	75.84	75.83	.01	75.49	75.30	.19	75.57	75.21	.36	75.57	75.40	.17	77.21	77.28	-.07	77.40	77.58	-.18	78.02	78.01	.01	77.73	77.87	-.14
21	02-21-92	79.51	79.43	.08	79.32	79.07	.25	79.36	79.10	.26	79.41	79.16	.25	80.69	80.69	.00	80.91	81.06	-.15	80.20	80.16	.04	80.75	80.87	-.12
22	02-28-92	78.86	78.78	.08	78.74	78.45	.29	78.75	78.52	.23	78.78	78.50	.28	79.19	79.19	.00	79.29	79.45	-.16	79.61	79.58	.03	79.46	79.50	-.04
23	03-05-92	78.63	78.50	.13	78.62	78.16	.46	78.56	78.22	.34	78.59	78.20	.39	79.00	78.91	.09	79.12	79.17	-.05	79.46	79.38	.08	79.32	79.33	-.01
24	03-16-92	76.80	76.75	.05	76.50	76.18	.32	76.52	76.24	.28	76.57	76.23	.34	78.11	78.08	.03	78.32	78.47	-.15	78.79	78.74	.05	78.55	78.64	-.09
25	04-29-92	79.02	78.79	.23	78.77	78.64	.13	78.81	78.52	.29	78.88	78.24	.64	80.27	79.98	.29	80.47	80.46	.01	80.50	80.18	.32	80.50	80.41	.09
26	05-27-92	79.71	79.42	.29	79.41	79.20	.21	79.46	82.03	-2.57	79.51	79.51	.00	81.82	81.61	.21	81.86	82.07	-.21	86.96	87.13	-.17	82.74	82.61	.13
27	06-01-92	86.35	86.10	.25	86.63	86.45	.18	86.63	89.44	-2.81	86.66	85.99	.67	85.83	85.50	.33	85.66	85.77	-.11	86.35	86.61	-.26	85.76	85.68	.08
28	06-25-92	80.76	80.70	.06	80.34	80.25	.09	80.42	83.29	-2.87	80.46	79.91	.55	82.15	81.83	.32	82.29	82.47	-.18	84.69	84.81	-.12	82.82	82.77	.05
29	07-20-92	80.28	80.20	.08	79.90	79.87	.03	79.95	79.91	.04	80.01	79.99	.02	81.97	81.95	.02	81.99	81.97	.02	84.12	84.11	.01	82.40	82.39	.01
30	07-30-92	79.95	79.97	-.02	79.56	79.58	-.02	79.62	79.60	.02	79.69	79.62	.07	81.62	81.67	-.05	81.67	81.64	.03	83.63	83.69	-.06	82.07	82.07	.00

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Installation of the Paroscientific Submersible Transducer

By Andrew W. Records[1]

The installation of the Paroscientific submersible transducer is in general the same as for other submersible transducers. The submersible tranducer is relatively easy to install because it does not require a nitrogen gas source; tank changes or gas leaks are not a concern. Slope changes are not needed to correct for elevation, length of orifice line, or change in stage. A submersible type of transducer is also easily adapted to a packer installation in which sections of a well or borehole need to be isolated from other parts of the hole or from the atmosphere. There are two types of submersible transducers: differential and absolute.

The differential transducer, which is vented to the atmosphere, does not require compensation for barometric pressure. The transducer requires cable with a vent tube that becomes costly when long cables are needed. Splices can be made on vented cable, but leaks are common. Moisture must not be allowed into the vent tube, so desiccant containers or dry-air bottles are installed on the vent tube end.

The absolute transducer is an alternative to the differential type if cable cost is prohibitive. Having no vent tube, absolute-transducer cable can be spliced easily for longer cable runs. The cable is unaffected by sharp bends or kinks, so cable placement is less critical. One of the major drawbacks of the absolute transducer is that it is sealed from the atmosphere when submerged. Unless barometric response is negligible compared to stage, the barometric response must be removed from the signal. This is done by simultaneously recording barometric pressure with a barometer having the same resolution and accuracy as the stage measurement. If this is not possible, recordings from a barometer at a nearby site can be used to filter out most major atmospheric effects.

The pressure range of the transducer is matched to the expected conditions at the site. The lowest transducer pressure range necessary to cover the expected variation in stage will give the best resolution. A range of 0 to 5 pounds per square inch will give the best resolution for small strain events or tidal influences. Adequate for most hydrologic work, ranges of 0 to 15 or 0 to 30 pounds per square inch will give a good resolution. However, if the variation in stage exceeds 1.2 times the tranducer overpressure rating, a higher-pressure transducer must be used. Units with a range of 0 to 100 pounds per square inch have been used in wells and reservoirs, but with some loss of resolution.

To install the Paroscientific transducer, a holder bracket is attached to the transducer housing. The Seacon connector found on most Paroscientific units is adequate to hold the transducer, but a holder bracket is far more secure. A tapped one-quarter inch hole is provided by the manufacturer at the bottom of the transducer housing where the bracket is attached. If the transducer is installed in saline water, then a sacrificial zinc element is also attached to the bracket and only stainless steel cable, clamps, and thimbles are used in the installation.

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[2] Use of trade names is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey

Signal output of the transducer ranges in frequency from 30 to 42 kilohertz. The signal is usually sent to an intelligent card to produce a specific, user-friendly type of output. Intelligent cards offered include SDI-12, RS-232, 16-bit binary, and 4-20 milliampere signal versions; the cards can be installed in the transducer housing to make a neat package. The 4-20 milliampere signal is used for long runs of cable. The SDI-12 signal is compatible with many data loggers and data collection platforms used by the U.S. Geological Survey. The RS-232 signal is commonly used in computers and modems, and the 16-bit binary type is used in some SCADA systems and other equipment. If more than one type of signal is needed, the transducer output can be split and sent to two different cards. Two separate loggers, modems, or data-collection platforms can then interrogate the transducer at the same time.

Current-Mode Operation of a Silicon Diaphragm Pressure Transducer for Measuring Pneumatic Pressure

By Joseph P. Rousseau[1]

INTRODUCTION

Druck[2] PDCR 930U, silicon diaphragm, strain gage, pressure transducers are being used to measure *in-situ* pneumatic pressure in deep boreholes (up to 750 meters) at Yucca Mountain, Nye County, Nevada. Measurements of pneumatic pressure are being made to characterize gaseous-phase flow-processes in the unsaturated zone. The device in use, is rated by the manufacturer for operation over an absolute pressure range of 0 to 70 kPa. To maximize sensitivity, the device is calibrated by the U.S.G.S and operated in an over-range condition, 70 to 115 kPa. Rated burst pressure is 3X's full range or 210 kPa. The calibrated accuracy of this sensor is better than 0.03%, and its sensitivity is better than 0.003% full scale (115 kPa).

OPERATION

The calibrated sensor is operated by using a constant current to power the strain-gage element. When current is used to excite the sensor, voltage is allowed to float to whatever potential (within pre-specified, voltage-compliance limits of the current source) is needed to provide a constant current to the sensor. Current is provided by a Keithley[2] 220 current generator; and voltage output is measured with a Hewlett Packard[2] 3457A multimeter. Constant current excitation eliminates 1) measurement errors caused by uncontrolled voltage drops across long lead-wires and, 2) the need to calibrate these sensors with lead wires attached. Current excitation settings (approximately 2.4 to 2.7 milliamps) are determined independently for each sensor in order to provide a voltage drop across the strain gage element that is as close as possible to the rated excitation voltage (10 volts) of the sensor as recommended by the manufacturer. This is done in order to maintain the sensitivity of the device.

CALIBRATION

Calibrations are conducted over a restricted range of temperature (5 to 50°C) and pressure (70 to 115 kPa) to optimize the performance of these sensors for their intended application. The sensors that are used to measure *in-situ* pneumatic pressure at Yucca Mountain do not incorporate internal, temperature-compensation circuitry. Instead, temperature is carried as an independent calibration parameter and is measured using glass-encapsulated bead thermistors that are co-located with the pressure transducers. Calibrations are conducted in a constant temperature water bath. The regression model used to fit the calibration data for this device is a second order polynomial of the form:

$$P = A + B(mV) + C(mV)T + D(T^2) + E(T)$$

where:

P = pressure in Pascals
mV = voltage in millivolts
T = temperature in °C
A, B, C, D, E = coefficients derived from measurements using a multiple, non-linear regression routine.

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[2] Use of trade or manufacturer names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Approximately 720 voltage measurements at different temperatures and pressures are used to compute the calibration coefficients for each sensor. All coefficients in the regression model are statistically significant with t-ratios much greater than three.

The minimum acceptable calibration accuracy (95% confidence) of these sensors, is for use in the deep, unsaturated-zone, borehole-instrumentation program at Yucca Mountain, is ± 0.035 kPa (0.03% full scale) although accuracies of ± 0.020 kPa (0.02%) are readily achievable. A deadweight, piston, pressure gage, with an accuracy of 0.015%, is used to calibrate these sensors.

Tests were conducted to determine the effects of long lead-wires (up to 800 meters in length) on the calibration coefficients of these sensors when operated in current mode. The resulting calibration coefficients were statistically identical to those derived from calibrating the same sensors over lead-wire lengths of 2 meters.

FIELD TESTING

A long-term, on-going, field-test of these sensors was initiated in October, 1991 with the installation of twenty-four Druck PDCR 930U pressure transducers in three shallow (12.1 meter deep), cased and backfilled, screened boreholes. Units were deployed in pairs with one unit designated as the primary sensor and the other as the alternate or backup sensor. Primary sensors have been operated once every three to five hours; and alternate sensors periodically to confirm the pressure reading of the primary sensor. Each primary sensor has undergone over 4500 duty cycles; alternate sensors have undergone approximately 1000 duty cycles. The long-term stability characteristics of these sensors have been confirmed by comparing simultaneous measurements of pressure made by each primary sensor with that of its counterpart (or alternate) sensor. With the exception of one sensor, all primary and alternate sensors have corroborated pressure measurements that are within the original calibration tolerances of these units, i.e., ± 20 Pa. The results of these field trials also indicate that the sensitivity of these sensors is on the order of 1 to 3 Pa (0.001 to 0.003% of full scale).

Using the Druck PDCR 930U, soil-gas pressure changes, induced by daytime heating (pressure decreasing) and nighttime cooling (pressure increasing) of the atmosphere, have been detected down to depths of 12.1 meters. In the absence of a deeper, subsurface confining layer, to impede downward propagation of atmospheric pressure changes at the ground surface, it should be possible to detect the effects of diurnal atmospheric changes down to depths as great as 50 meters using this sensor.

SUMMARY

Constant-current excitation of the Druck[2] PDCR 930U pressure transducer has eliminated a source of measurement error that would normally be encountered in attempting to operate these sensors with voltage excitation, over long lead-wires. The accuracy, sensitivity, and long-term stability of these units have been confirmed in laboratory experiments and in long-term (2 1/2 years) field trials. The performance of these units may be limited by the accuracy and precision of the electronics used and by the accuracy of the primary standard (Ruska[2] Model 2465 deadweight tester - 0.015% accuracy) used to calibrate these sensors.

Evaluation of Digital Pressure Sensors Used to Measure Water Levels at the Nevada Test Site, Nye County, Nevada, 1990-93

By R. Wolfgang Unger[1]

Water-level measurement at the Nevada Test Site (NTS) is affected by several factors that intensify labor requirements for data collection. Factors include great depths to the water table (hundreds to thousands of feet below land surface), large distances between wells (several tens of miles), diversity of well construction and weather conditions, and other environmental factors. Another concern is the need to avoid contamination of boreholes and cross-contamination of hydrogeologic units penetrated by boreholes. Analog sensors proved to be deficient; long-term use of these sensors led to equipment drift, interference anomalies, and ineffectual long-term data collection and processing. Analog sensors provided accurate and dependable short-term data from shallow wells, but had problems with data transfer during deep-well measurements.

Use of digital pressure sensors (DPS) for continuous monitoring of water levels in deep wells at NTS was evaluated during 1990-93. DPS are transducers that operate using a digital bit stream for communicating with data loggers. The evaluation was made by installing digital sensors in wells to continuously monitor small-magnitude changes in water level due to pumping and to natural aquifer response. DPS have shown increased effectiveness in collecting water-level data in wells where the water tables are at great depths.

The sensors were set in wells and left unattended except for monthly site inspections and data collection. Measurements of water levels, using steel reference or electric tapes, were compared to sensor output to verify the accuracy of DPS.

Digital sensors gave superior performance relative to analog sensors by providing continuous, high quality water-level data. DPS provide improved, drift-free data for deep-well measurements; are compatible with U.S. Geological Survey wireline equipment; and are highly reliable and accurate. Sensors rated at 15 pounds per square inch are capable of resolving 0.007 foot of head change with an error accuracy of 0.006 percent (meeting program guidelines of 0.1 foot and 0.01 percent, respectively).

The use of digital sensors has significantly improved the efficiency of water-level data collection at NTS. Intensified labor requirements are effectively mitigated by digital sensors. Digital sensors can be left unattended for long periods. Great depths to the water table, large distances between wells, diversity of well construction and weather conditions, and potential for hydrogeological cross-contamination are no longer significant encumbrances to water-level data collection.

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[1] U.S. Geological Survey, WRD, 6770 S. Paradise Road, Las Vegas, Nevada 89119.

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Correction of Water-level Data From A Submersible Pressure Transducer Collected Using Erroneous Transducer Coefficients

By: Kenneth R Watts[1]

Submersible pressure transducers and programmable data loggers can greatly increase the frequency and accuracy of water-level measurements during early time of slug tests; however, if transducer coefficients are programmed incorrectly or calibration checks of the transducer indicate that transducer coefficients were incorrect, then analysis of the slug-test data could result in invalid estimates of hydraulic characteristics. Conversion of a transducer's electrical signal by a data logger to units of pressure commonly is done using a quadratic or a linear equation and user-defined values of the transducer coefficients. Water-level data that are collected using invalid transducer coefficients can be corrected by converting the water-level data back to the original transducer output (milliamperes or millivolts) and then recalculating the water levels using the correct transducer coefficients.

A general form of a quadratic equation for converting the electrical output from a transducer to units of pressure is

$$ax^2 + bx + c = y \qquad \text{(eq. 1),}$$

where: a, b, and c, are the transducer coefficients; x is the transducer output in milliamperes; and y is the transducer output in units of pressure (pounds per square inch). If a linear equation is used, $a = 0$ and equation 1 simplifies to

$$bx + c = y \qquad \text{(eq. 2).}$$

To convert transducer output from units of pressure, in pounds per square inch, to feet of water, both sides of equation 1 or 2 can be multiplied by a constant (2.3067 feet of water = 1 pound per square inch).

The solution of equation 1 for x is

$$x = -b \pm \frac{\sqrt{b^2 - 4a(c-y)}}{2a} \qquad \text{(eq. 3).}$$

The solution of equation 2 for x is

$$x = \frac{y-c}{b} \qquad \text{(eq. 4).}$$

The coefficients a, b, and c are determined by calibration of the transducer and are defined as follows: the linearity coefficient a is the incremental error in the transducer; the scale coefficient b is the pressure of the transducer at full scale response; and the offset coefficient c is the error in measurement at zero pressure.

Water-level data collected during a slug test with a submersible pressure transducer and programmable data logger are listed in table 3 and shown in figure 9. Coefficients were altered to test the effects of using incorrect coefficients in the equation to convert transducer output to units of pressure. The results of using erroneous coefficients also are listed in table 3 and shown in figure 9. The erroneous data sets were calculated by: (1) converting the correct transducer output, in feet of water, to pounds per square inch; (2) solving

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equation 3 to convert from pounds per square inch to milliamperes; (3) calculating erroneous values of pressure in pounds per square inch using equation 1, an erroneous value of one of the coefficients, and the transducer output in milliamperes; and (4) converting the erroneous output, in pounds per square inch, to feet of water. The calibrated coefficients for the transducer used in the slug test were: $a = 0.0024$, b=10.0605, and $c = -0.1157$. Invalid values for the transducer coefficients used to calculate the erroneous water-level data sets are underlined in the following sets of coefficients: (1) $\underline{a = 0.024}$, $b = 10.0605$, and c =- 0.1157; (2) $a = 0.0024$, $\underline{b = 10.605}$, and $c = -0.1157$; and (3) $a = 0.0024$, $b = 10.0605$, and $\underline{c = 0}$.

The constant error caused by use of an invalid offset coefficient c in set 3 is large (0.267 feet) and is equal to the product of the constant for conversion from pressure in pounds per square inch to feet of water (2.307 feet per pound per square inch) and the error in the offset coefficient (0.1157 pounds per square inch). Error in the offset coefficient c is easily recognized in water-level data from slug tests because the error is constant throughout the test. Errors in the linearity coefficient a and scale coefficient b are not as obvious, when reviewing water-level data, because their effects are proportional to the magnitude of the pressure, and large errors would occur only if the pressure was large and the linearity and scale coefficients were greatly in error. Erroneous transducer coefficients used in programmable data loggers could result in substantial errors in the water-level data and subsequent analyses of these data. However, erroneous data can be corrected using simple algebraic equations.

Table 3. Example slug-test data with correct and incorrect transducer coefficients

Elapsed time (second)	Measured water-level change (foot)	Hypothetical water-level change (foot)		
		Linearity [1]	Scale [2]	Offset [3]
1	0.905	0.937	0.968	1.172
3	.735	.759	.789	1.002
6	.518	.533	.560	.785
7.5	.474	.487	.514	.741
9	.429	.440	.467	.696
10.5	.391	.401	.427	.658
12	.353	.362	.387	.620
15	.289	.296	.319	.556
16.5	.267	.274	.296	.534
18	.242	.248	.270	.509
21	.200	.205	.225	.467
24	.165	.169	.188	.432
27	.140	.144	.162	.407
30	.118	.122	.139	.385
33	.099	.102	.119	.366
36	.083	.086	.102	.350
39	.070	.073	.088	.337
42	.060	.063	.078	.327
45	.051	.053	.068	.318
48	.045	.047	.062	.312
51	.038	.040	.054	.305
54	.032	.034	.048	.299
57	.029	.031	.045	.296
60	.022	.024	.038	.289

[1] Correct linearity coefficient, $a = 0.0024$, incorrect $a = 0.024$.

[2] Correct scale coefficient, $b = 10.0605$, incorrect $b = 10.605$.

[3] Correct offset coefficient, $c = -0.1157$, incorrect $c = 0.0$

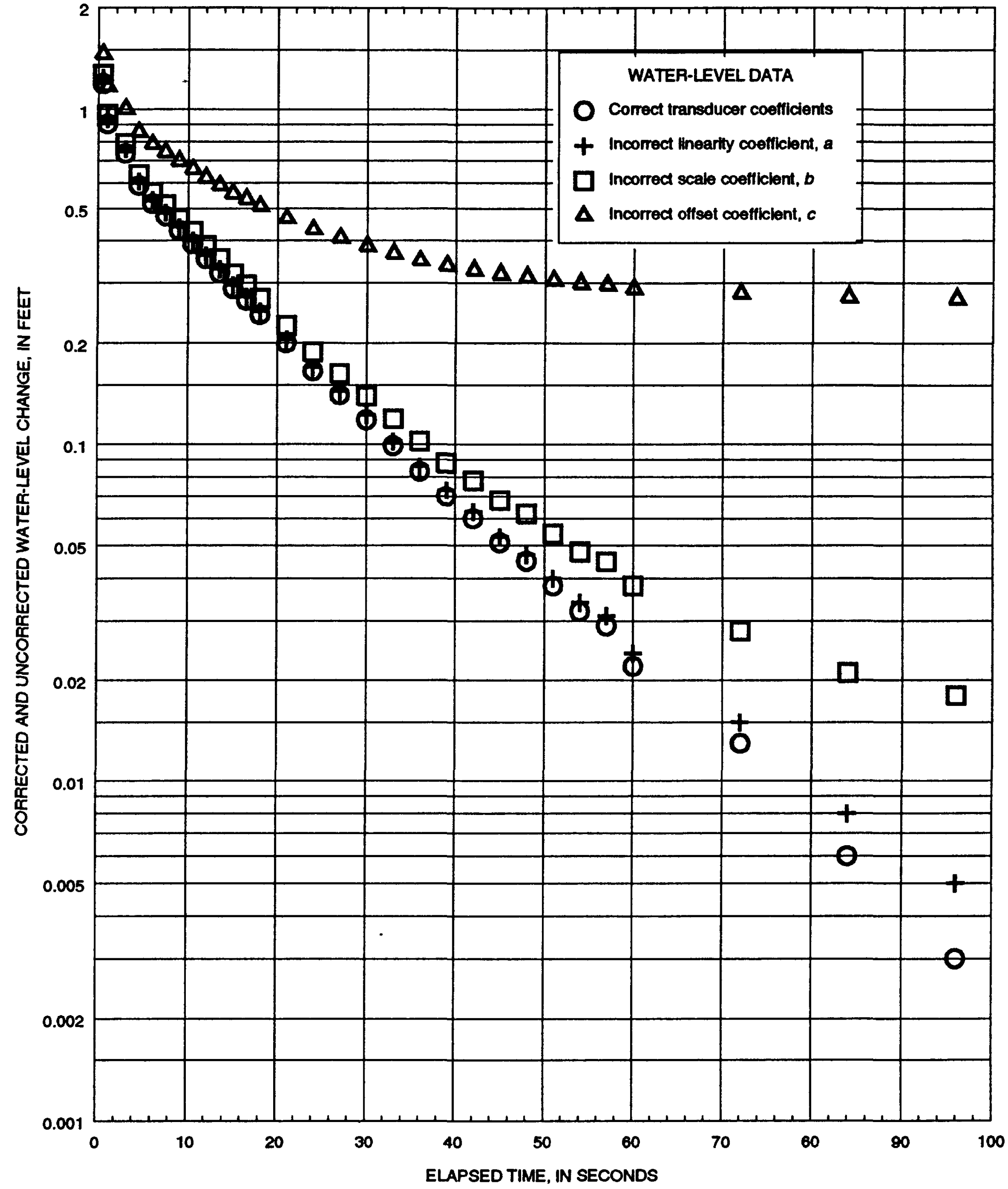

Figure 9. Slug-test data with correct and incorrect transducer coefficients. [NOTE: Additional data are shown in figure 9 that are not included in table 3.]

Pressure Transducers Used in Monitoring Ground Water Levels for the Central Valley Aquifer Project at the Zamora Well Site, Yolo County, California

by Michael D. Webster[1]

The U.S. Geological Survey currently operates three continuously monitored ground-water sites for the Central Valley Aquifer Project. The sites are in the Sacramento Valley near the towns of Zamora, Nicholas, and Butte City. Each site consists of three multi-depth wells. Data from these sites are recorded on Campbell Scientific CR-10 data loggers. Water-level sensors used have included Handar 436A and 436B shaft encoders at the Nicholas and Butte City sites and GeoKon vibrating wire pressure transducers and Design Analysis H300 pressure transducers at the Zamora site.

The Zamora site is 4 miles northeast of the town of Zamora in Yolo County. Well 1 is screened in alluvium at 2,120 to 2,125 feet below land surface datum (LSD), well 2 at 1,396 to 1,401 feet below LSD, and well 3 at 942 to 947 feet below LSD. Yearly water-level changes normally range from less than 1 foot for well 1 to about 12 feet for well 3. Although only well 1 is currently artesian, all three wells have flowed at times. Head above LSD for the period of record was 4.43 feet on September 19, 1988, in well 1; 6.74 feet on September 6, 1988, in well 2; and 2.16 feet May 3-5, 1984, in well 3. Because these wells have been artesian, transducers were used to monitor water levels because of the mechanics of installation as compared with float operated systems.

Continuous data collection began in the 1979 water year using Leupold and Stevens Type-F analog recorders and floats. In the 1989 water year, a CR-10 data logger and three 10-pound-per-square-inch (psi) GeoKon vibrating wire, ambient pressure transducers were installed to monitor water levels continuously. A fourth 5-psi GeoKon transducer was installed to measure barometric pressure contin-uously. The barometric pressures were then used to adjust water-level measurements for the effects of atmospheric pressure changes. These transducers were fairly reliable, with only one transducer failure during 3 years of operation. Accuracies for 1989 through 1992 water years were within +/-0.1 foot.

On February 25, 1993, the GeoKon system was replaced with a SDI-12 (serial digital inter-face, 12VDC, 1200 baud) system using an up-graded CR-10 data logger and three Design Analysis H300 vented pressure transducers. A cellular phone system also was installed for data retrieval and gage-monitoring purposes. Because these transducers are vented to the atmosphere, corrections are not needed for atmospheric pres-sure changes. From the date of installation until May 11, 1994, the difference between measured water-levels and recorded levels ranged from +0.14 to -0.07 foot. These differences were corrected on a time-proration basis and did not seem to follow a trend, although temperature, method of suspension, subsidence, and electronic drift could all have an effect on the accuracy of the water-level record. The reliability and accuracy of the GeoKon vibrating wire and the Design Analysis H300 transducers are adequate for the type of data collection required at the Zamora site.

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APPENDIXES

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APPENDIX 1. VENDORS AND EXHIBITORS

Company	Representative
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GeoKon, Inc. 48 Spencer Street Lebanon, NH 03766	Barry Sellers
Instrumentation Northwest 10518 North Iroquois Drive Spokane, WA 99208	Mike Kirsch
Paroscientific, Inc. 4500 148th Avenue, NE Redmond, WA 98502	Russ Hanson
Resource International 2804 Churchbell Court Mobile, AL 36695 (distributor for Rittmeyer)	Phil Orrill Hans-Peter Vaterlaus (Rittmeyer)

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APPENDIX 2. WORKSHOP ATTENDEES

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Robert E. Faye	Regional Ground-Water Specialist, Norcross, Georgia
Lawrence A. Freeman	Hydrologic Technican, Sacramento, California
Gerard J. Gonthier	Hydrologist, Little Rock, Arkansas
Kenneth J. Hollett	Assistant Chief, Office of Ground Water, Reston, Virginia
Vito J. Latkovich	Chief, Hydrologic Instrumentation Facility, Stennis Space Center, Mississippi
Raymond A. Mularoni	Hydrologic Technican, Tampa, Florida
Nathan C. Myers	Hydrologist, Lawrence, Kansas
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Keith Overton	Hydrologic Technican, Saint Thomas, Virgin Islands
Gary L. Patterson	Hydrologist, Yucca Mountain Project Branch, Lakewood, Colorado
Keith R. Prince	Regional Ground-Water Specialist, Menlo Park, California
Andrew W. Records	Hydrologic Technician, Tacoma, Washington
Donald O. Rosenberry	Research Hydrologist, Lakewood, Colorado
Joseph P. Rousseau	Electronics Engineer, Yucca Mountain Project Branch, Lakewood, Colorado
Albert T. Rutledge	Regional Ground-Water Specialist, Reston, Virginia
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Sammy L. Wilbourn	Engineering Technican, Hydrologic Instrumentation Facility, Stennis Space Center, Mississippi
Randall W. Unger	Hydrologist, Las Vegas, Nevada
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Kenneth R. Watts	Hydrologist, Pueblo, Colorado
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