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Hydrometry — Measuring the water level in a well using automated pressure transducer methods

Hydrométrie — Méthodes automatisées, utilisant des transducteurs de pression, pour mesurer le niveau d'eau dans un puits

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Foreword

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In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

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ISO/TR 23211 was prepared by Technical Committee ISO/TC 113, *Hydrometry*, Subcommittee SC 8, *Ground water*.

This Technical Report is based on, and much of the material is from, Freeman and others [8]. It complements ISO 4373, *Hydrometry — Water level measuring devices*.

Introduction

Submersible pressure transducers, developed in the early 1960s, have made the collection of water-level and pressure data much more convenient than former methods. Submersible pressure transducers, when combined with electronic data recorders have made it possible to collect continuous or nearly continuous water-level or pressure data from wells, piezometers, soil-moisture tensiometers, and surface water gages. These more frequent measurements have led to an improved understanding of the hydraulic processes in streams, soils, and aquifers.

Hydrometry — Measuring the water level in a well using automated pressure transducer methods

1 Scope

This Technical Report provides information about the functional requirements of instrumentation for measuring the water level in a well using automated pressure transducer methods.

This Technical Report provides guidance for the proper selection, installation and operation of submersible pressure transducers and data loggers for the collection of hydrologic data, primarily for the collection of water-level data from wells. Basic principles, measurement needs and considerations for operating submersible pressure transducers are described and the systematic errors inherent in their use are discussed. Standard operational procedures for data collection and data processing, as well as applications of transducers for specific types of hydrologic investigations are included. Basic concepts regarding the physics of pressure and the mechanics of measuring pressure are presented, along with information on the electronics used to make and record these measurements. Guidelines for transducer calibration, proper use and quality assurance of data also are presented. Ground water field applications of pressure transducer systems are discussed, as are common problems that may corrupt data, along with suggestions for field repairs.

Annex A provides guidance on the types of pressure transducers commonly used for water-level measurement and the measurement uncertainty associated with them.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 772, *Hydrometry — Vocabulary and symbols*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 772 apply.

4 Applications of the use of pressure transducers to ground-water resource investigations

4.1 Ground-water monitoring

Submersible pressure transducers can be used for long-term and short-term applications. This clause discusses both applications. In addition, in 4.4, information is provided on the technique of reducing well-bore storage so that the user can apply this technique to reduce the effective diameter of wells during slug tests or aquifer tests.

4.2 Long-term monitoring

4.2.1 General

Many hydrologic investigations require continual monitoring (over periods of weeks to years) of water levels in wells. Examples of such studies include monitoring water levels for

— indication of earth tides [10], [16],

— indication of earthquakes [6], [26],

— determination of temporal variation in vertical or horizontal hydraulic gradients [11], [28],

— determination of timing and magnitude of recharge to ground water following precipitation events [23], [28], and

— monitoring of pump-and-treat operations at ground-water reclamation sites.

For many studies, even if continual data collection is not necessary, it is cost effective to monitor water-level fluctuations in wells with a sensor rather than using human resources to collect discrete measurements.

Submersible pressure transducers have long been used for monitoring water-level fluctuations in wells [11], [29]. Buried in the soil, these devices also have been used for decades to monitor pressure heads. Sensors used in this way have historically been called the “Casagrande type” pressure transducers, and are commonly used to monitor pressure heads in and around dams. While other automated water-level sensor systems also can provide continual water-level data in wells, submersible pressure transducers are particularly well suited for some applications. Typically small, and requiring little maintenance because they are immersed in water, their environmental conditions are relatively stable. Some examples of applications in which submersible pressure transducers are particularly well suited are listed below.

4.2.2 Pressure range considerations

Submersible pressure transducers can be selected to monitor a small or large range of expected water-level conditions. Transducers designed to measure a small pressure range can monitor stage changes of 3 m (10 ft) or less with a very high degree of resolution and accuracy. However, higher range pressure transducers can monitor water level changes on the order of 100 m (300 ft) with little loss of resolution or accuracy. Pressure transducers are well suited when large and sometimes rapid stage changes are expected, such as monitoring head changes in karst terrain, production wells, or pressure pulses associated with earthquakes.

4.2.3 Non-vertical or irregular situations

Submersible pressure transducers can be used in non-vertical or irregular wells when other systems cannot operate effectively. For a non-vertical well, a properly calibrated pressure transducer will indicate changes in vertical head in the well, requiring no adjustment to the data, whereas data from a float installed in the same well would require adjustment to compensate for the well’s non-vertical orientation. Also, severe irregularities or deviations in the bore of a well could render acoustic-velocity devices or float mechanisms inoperative, while data from a pressure transducer would not be affected.

4.2.4 Severe environments

Submersible pressure transducers are well suited for data collection in severe environmental conditions, such as arctic or low-latitude desert climates. The relative stability of ground-water temperature provides a much more suitable environment for submersible pressure transducers than for sensors that are mounted above ground or inside a well but above the water table. During freezing conditions, other types of sensors mounted to the top of a well can be disabled by freezing of water that has condensed on the sensor [28]. Not only is the submersible pressure transducer usually not exposed to such extreme temperatures, if the water level in the well is shallow enough to freeze, the pressure transducer can continue to register pressure fluctuations below the ice lens. If ice were present in the well, an acoustic-velocity system or a float would indicate a constant water level. Relic ice lenses still frozen to the side of a well can hinder the operation of sensors.

4.2.5 Flowing wells

In flowing artesian wells (wells with potentiometric heads above land surface), a submersible pressure transducer can provide potentiometric-head data. This transducer is especially well suited to provide data when the potentiometric head fluctuates both above and below land surface. If potentiometric head rises to the point where a standpipe is impractical, or if heads frequently drop below land surface, a submersible pressure transducer may be the only practical option for providing continuous potentiometric-head data.

4.2.6 Large depth-to-water considerations

Wells with a depth to water greater than 100 m (300 ft) present special problems for most submersible pressure transducers. Cable or line stretch, thermal expansion, vent-tube blockage, and signal loss can introduce significant errors in deep wells or where sensors are located far from a logging device. O'Brien [24] noted that voltage problems caused by lead lengths of up to 1 500 m (5 000 ft), and blocked vent tubes, led to problems when monitoring water-level fluctuations in deep wells. Well-bore deviation, a problem common to deep wells, is magnified by the depth to water. Submersible pressure transducer models capable of making an analogue to digital conversion before transmitting the signal up the well to the data logger can overcome many of these problems.

4.2.7 Small diameter situations

To mitigate problems associated with hydraulic lag time, small-diameter piezometers commonly are installed in wells drilled in geologic materials with low hydraulic conductivity. Although other types of sensors have been used for monitoring water-level fluctuations in small-diameter wells [21], most sensors are too large to fit inside wells with a diameter much smaller than about 2,54 cm (1 in). Vibrating wire pressure transducers small enough to fit inside wells as small as 1,27 cm (0,5 in) can provide reliable data when some other sensor types cannot.

4.2.8 Marsh installations

Water levels in wells installed in easily compressed materials, such as those in a salt marsh or a fen, can be altered by a person walking on the surface so that the water levels recorded during site visits are not representative of a site’s long-term conditions. Frequently, these wells are of small diameter to minimize hydraulic lag time associated with low hydraulic conductivity materials. Submersible pressure transducers have been used to provide unaltered hydraulic-head data during intervals between site visits [28].

4.2.9 Buried installation

Submersible pressure transducers have been used to monitor pore pressure at earth-filled dams and in slope-stability studies. Buried transducers can provide pore-pressure data without the aid of a well. Carpenter and others [3] buried submersible pressure transducers in sandbars to monitor pore-pressure fluctuations in response to significant stage changes of a river. The sensors were installed in areas where wells would not have been feasible because the river periodically inundated the sandbar.

4.2.10 Multiple zone measurements

Submersible pressure transducers are convenient when making multiple-zone pressure-head measurements in open boreholes containing packers that isolate intervals of the borehole. Transducers can be connected to threaded tubes that pass through the packers and register pressure head of isolated intervals without requiring the transducer to be located in those intervals [15][25]. This type of connection can reduce complexity, borehole clutter and cost.

4.2.11 Conclusion

As shown in the previous discussion, submersible pressure transducers are well suited for many hydrologic applications; however, their use for long-term monitoring of water levels occasionally can lead to errors if data are not corroborated. The convenience and low maintenance of submersible pressure transducers can lead to long intervals between calibration checks and overconfidence in the reliability of the sensor's data. If checks on the calibration of sensors are not made, data may be erroneous to the point of leading to incorrect hydrologic interpretations. A study of vertical hydraulic head gradients at a well nest showed that uncorrected data from submersible pressure transducers resulted in an interpretation of reversals in vertical hydraulic-head gradients when none actually occurred [28]. Linear adjustment of data based on monthly check measurements would have led to the conclusion that additional water-table fluctuations of up to 0,052 m (0,17 ft) occurred when weekly check measurements indicated that sensor drift actually was responsible for those interpreted water-level fluctuations.

Gage pressure transducers usually are used to measure pressure in a water body open to the atmosphere, whereas absolute transducers usually are used as barometers and in sealed environments such as below packers. The user may wish to substitute absolute transducers for gage transducers to eliminate the need for vented cable, especially to multiple transducers in close proximity, connected to one data logger. A barometer, which can be an identical inexpensive absolute transducer, also must be operated. When using an absolute transducer in a gage transducer application, subtract the barometric record from the water-level record to get submergence. Three redundant barometers can be used in conjunction with many absolute transducers measuring water levels. Because the adjusted record is the difference between two records, noise and drift that are not common to both transducers may increase by as much as a factor of two.

An absolute transducer can also be used instead of a gage transducer to measure changes in wells in aquifers with barometric efficiencies close to 100 %. After verifying that the barometric efficiency is indeed close to 100 %, the original record from the absolute transducer is acceptable as the "barometrically adjusted" record.

4.3 Short-term monitoring

Submersible pressure transducers have been used extensively for monitoring water-level fluctuations during single-well and multiple-well aquifer and slug tests. Before the use of automated sensors, aquifer tests were labour intensive, and early drawdown in the pumped well was not easily observed. Similarly, for single-well slug tests in sandy material, the early portion of the recovery commonly went unrecorded simply because it was not possible to get water-level measurements that were only seconds apart. Using submersible pressure transducers has reduced labour costs and has provided the opportunity to collect data frequently during the early portion of aquifer and slug tests. When combined with a programmable data logger, the pressure transducer can supply data frequently during the early portion of the test and less frequently as the test progresses and the recovery rate slows. For clean, coarse sand, when the recovery of a slug test can be completed in less than half a minute, the fast response of many types of submersible pressure transducers can allow measurement with a sampling interval of half a second or less.

The pressure transducer used for aquifer tests should be capable of reliably measuring the expected range of water-level fluctuations. For example, for an aquifer test, the pressure transducer in the pumped well should be capable of monitoring head changes much larger than is necessary for transducers installed in observation wells, where changes in water level are smaller and where greater accuracy may be desired. Similarly, for most single-well slug tests, a pressure transducer with a small pressure-sensitive range [such as 0 kPa to 34,5 kPa (0 psi to 5 psi)] is adequate.

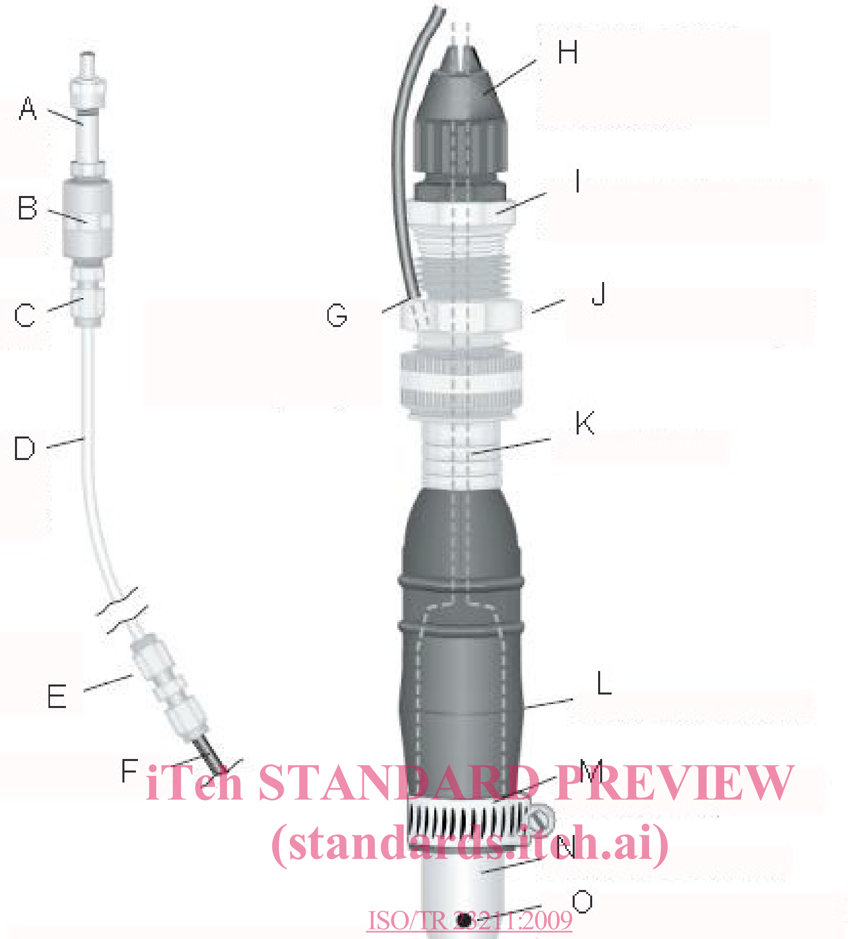
4.4 Reducing well-bore storage

Due to the movement of water from the well into the formation, the water level in a well or piezometer can lag behind head changes in the geologic formation. Typical situations in which this well-bore storage effect is most significant include slug tests, early time in drawdown or recovery during an aquifer test, and wells in low-permeability materials. Only in slug or bailing tests, in which a slug or water is rapidly introduced into, or withdrawn from, the well is the effect of reducing well-bore storage undesirable. In fact, analysing the decay of the residual water level in a well to determine hydraulic conductivity is the purpose of a slug test [20].

Packers that seal parts of wells to prevent flow within the borehole or to isolate zones for special tests sometimes are used to minimize the effects of well-bore storage in aquifer tests. Well-bore storage is, in effect, an incremental slug test superimposed upon the water-level fluctuation of interest during the test. An inexpensive packer that can be made in the field from materials from a hardware store or lumber yard (Figure 1) encloses the transducer and seals the piezometer. The appropriate transducer for this application is an absolute device because the transducer is sealed into a zone without access to atmospheric reference through the well. Drain cleaners that expand to more than 10 cm (4 in) are available; plumbing supply stores carry test seals of various kinds that can be made into packers. Straddle packers also can be assembled by using soldered copper tubing through brass fittings.

Small water-level differences between intervals separated by packers in a well can be measured with expensive, high-accuracy differential transducers that allow water in both ports or they can be measured as the difference between outputs of expensive high-accuracy absolute transducers. Alternatively, low-cost differential transducers that allow water in both ports can be used. In one case, pressure differences of several millimetres (a fraction of an inch) of water were measured between isolated intervals in a well at a submergence of more than 55 m (180 ft) using a differential transducer with a full-scale range of about 3 m (10 ft) of water. There was a large zero shift, but after establishing a new zero offset, valuable data were obtained at the beginning of the pumping period in spite of the fact that the pressure from submergence exceeded the overpressure specification by a factor of four and exceeded the specified range by a factor of 17.

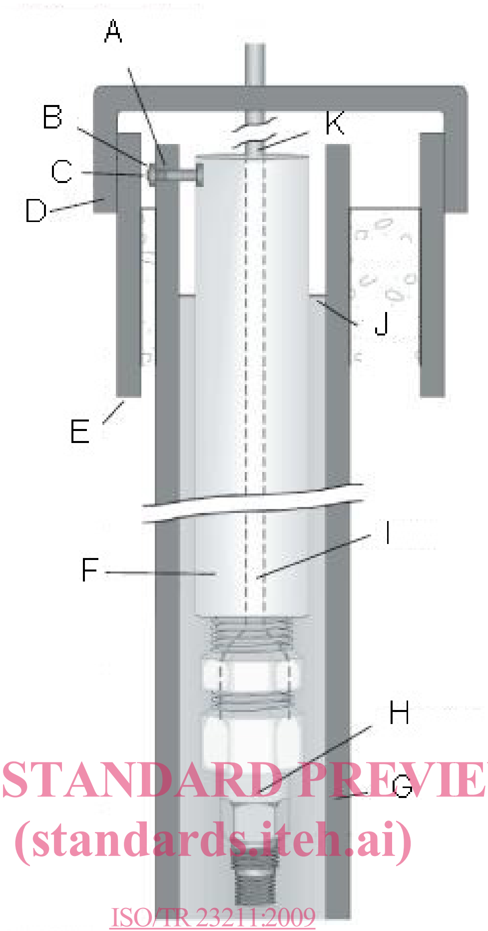
A drop pipe that occupies much of the cross-sectional area of a well can be used to reduce storage in a well bore (Figure 2). Advantages of this design include the ability to measure the water level in the well without removing the pipe, and the ability of the well to de-gas. For wells deeper than is practical for a standpipe from the surface, the pipe can be weighted, sealed at the top, and suspended by the transducer cable or a stainless-steel cable. To prevent a change in well-bore storage with changes in water level, the pipe must extend above and below possible water-level fluctuations. The appropriate transducer for this application is a differential or vented device because the transducer is in water open to the atmosphere.



Key

A valve to 6 mm (1/8 in) pipe fitting for pressure testing
B 6 mm (1/8 in) pipe coupling
C 6 mm (1/8 in) brass to 6 mm (1/8 in) male connector
D 6 mm (1/8 in) nylon tubing, extends to surface attached to transducer cable with nylon wire ties
E 6 mm (1/8 in) brass union (nylon ferrules can be substituted for brass ferrules)
F 6 mm (1/8 in) copper tubing
G fitting is drilled 6 mm (1/8 in), and 6 mm (1/8 in) copper tubing soldered for pressurizing packer gland
H strain relief – about 10 wraps of polytetrafluoroethylene tape should be used for strain-relief to female pipe joints
I 15 mm (1/2 in) to 10 mm (3/8 in) or 6 mm (1/4 in) threaded bushing if necessary
J 15 mm (1/2 in) brass female pipe to 20 mm (3/4 in) male hose fitting
K transducer cable
L drain cleaner packer gland
M hose clamp (brass tip of drain cleaner is removed)
N pressure transducer housing
O vent at transducer plane to prevent capture of air bubbles

Figure 1 — Packer based on drain-cleaner
(from Freeman and others [8], Figure 45)



Key

A well casing slotted vertically for bolt

B nut

C bolt

D locking cap

E surface casing, large enough to contain data logger, battery and peripherals in sealed box

F drop pipe, drilled at top for bolt, with female adapter and fitting of appropriate size at bottom to hold the transducer

For deep wells, the drop pipe can be fitted with ballast weight, sealed with a strain-relief fitting and bushings at the top, and hung using the cable. The drop pipe must span the range of water-level fluctuation to avoid a change in well-bore storage with water-level fluctuation.

G well

H transducer

I cable

J water table

K cable

Figure 2 — Drop-pipe protection of a submerged transducer
(from Freeman and others [8], Figure 46)

5 Planning considerations for sensor systems

5.1 General

The type and number of sensors and data recorders needed for automated collection of water-level data depend on the objectives of the study. Determine these objectives prior to selecting system components. Options are numerous, but once the study objectives and needs are clearly determined, the selection of appropriate system components will be simplified. Some considerations for planning the installation of a water-level collection system are presented below. For many installations, submersible pressure transducers may not be needed, nor may they be the most suitable water-level sensors. In the following subclauses, however, submersible pressure transducers are assumed to be the preferred water-level sensors.

5.2 Study duration and system reliability

Nearly all submersible pressure transducers are capable of providing accurate results for short-term studies (such as aquifer tests or slug tests) but as the study duration increases, the chance of sensor failure and the amount of zero drift increases. Purchasing more expensive sensors, engineered to withstand the added demands of long-term deployment, may be necessary. Sensor maintenance and recalibration also becomes a consideration when designing a long-term data-collection effort.

For long-term investigations, the data logger and power-supply systems need more attention and protection. It may be necessary to recondition and recalibrate the data logger occasionally or to house it in a dry environment to prevent failure of components due to long-term exposure to moisture. Sensor cables may need to be protected with tubing or pipe to prevent long-term damage from ultraviolet radiation, physical weathering, exposure to ozone, or vandalism.

System reliability is among the most important considerations when designing a water-level monitoring system to be operated over a long duration. Redundancy, designed into the system so a partial failure will not result in complete loss of data, can range from multiple sensors in the same borehole connected to one data logger to two or three completely separate systems logging water-level fluctuations in the same well. If a high degree of reliability is important, the study should be budgeted to provide early warning of system problems and fast access to replacement components to minimize down time.

Many manufacturers use terms such as mean time between failure and reliability to present durability information on their products. Mean time between failures is most commonly defined as the total time that a number of sensors operate, divided by the number of sensors that fail during the operational period. Reliability is the probability that an item will perform its intended function for a specified interval under stated conditions. Specified interval refers to the length of the study or test. Stated conditions refer to the operational environment — weather, humidity, temperature and electromagnetic interference. Most of the time, the specified interval or the stated conditions supplied by the manufacturer are not the same as those of the hydrologic investigation. Also, reliability specifications usually refer to a single component of what commonly is a multiple-component system. For example, a pressure transducer may have one stated reliability and a data logger may have a different stated reliability, and the reliability of the combination of the two components (the system reliability) will be different from either of the reliabilities of the individual components. Most of the time, the overall system reliability will approximate the reliability of the least-reliable component.

5.3 Required accuracy

Systems of pressure transducers, data loggers, cables and other supporting equipment used for sensing and recording water levels in wells must be sufficiently accurate to meet the needs of the project. A water-level sensing and recording system can be capable of performing within a measurement error of ± 3 mm (0,01 ft) for most water-level measurement applications. This measurement error may not be achievable for the case of large changes in water level (for example, during aquifer tests). An accuracy of 0,1 % of the expected range in water-level fluctuation would then be acceptable. Where the depth to water is greater than 30 m (100 ft), an accuracy of 0,01 % of the estimated depth to water is generally acceptable. In summary, the measurement error and accuracy standard for most situations are 3 mm (0,01 ft), 0,1 % of range in water-level fluctuation, or 0,01 % of depth to water above or below a measuring point, whichever is least restrictive. The subject of required accuracy is also discussed in ISO 4373.

While most sensor manufacturers produce devices that achieve acceptable accuracy, the added complexities of the wiring, data logger, power source and environmental variability may unacceptably degrade the overall system accuracy. Investigators may want to test the overall accuracy by conducting a pilot project before investing in a system that may not meet data objectives. In some cases, the desired accuracy may not be achievable with current technology or within budgetary constraints. For example, it is difficult to achieve a high level of accuracy with long leads, when depths to water are large, or when water-level fluctuations are large. Stringent accuracy constraints require frequent check measurements in the field.

5.4 Installation location and site accessibility

If the study site is nearby, then frequent visits to the site to download data, perform site maintenance, replace failed components, or make accuracy check measurements may be reasonable. If, however, the site is remote or difficult to access, then the system needs to be designed to be operated remotely and contain greater redundancy to better ensure uninterrupted collection of data. Remote sites may need an enhanced power supply, more robust shelters, extra data-storage capacity, equipment to allow communication with the site and transmission of data from the site, two or more transducers in a well, and automated checks for sensor drift.

5.5 System components and compatibility

When designing a data-collection system, determine which components are necessary and ensure that all of the components can communicate properly. Because power can be supplied by some data loggers, a short-term study might require only a pressure transducer connected to a data logger. For a long-term study, however, additional components including a power supply (batteries, solar panels, voltage regulator), additional data storage devices, a shelter or shelters, and a data-transmission system may be needed. Ensuring compatibility between components becomes more difficult as the number of components increases. For example, some data loggers cannot interpret a digital signal from a transducer that makes an analogue-to-digital conversion at the sensor. Similarly, the type of analogue signal needs to be compatible; if the sensor sends an amperage signal, the data logger needs to be able to receive an amperage signal. Some pressure transducers require a separate measurement of temperature in order to correct the transducer output for changes in temperature in the well. If a data logger is not capable of receiving the temperature signal, the overall system accuracy is reduced. The data logger must also be able to supply the excitation voltage or current required by the sensor. When designing the installation, the number of sensors the data logger can simultaneously record needs to be considered.

5.6 Water quality

Water quality must be considered when planning an installation. If the well will be used for water-quality sampling, the transducer and cable should be easy to clean before installing. Do not use lead or plastic-coated lead weights to apply tension to the cable. If the well is at a contaminated site, consider the possible effects of contaminants in the water that may corrode or otherwise degrade transducer components. Select components that are corrosion resistant and easily decontaminated. Some manufacturers make chemical-resistant transducers of stainless steel or titanium, and polytetrafluoroethylene-coated cables.

5.7 Number of wells

For several wells in close proximity – for example, a nest of piezometers or multiple wells for a pumping test – one data logger that can receive signals from several pressure transducers usually is much less expensive than dedicating a data logger to each sensor. Data retrieval from one data logger also is much simpler. Instrumentation of many wells requires many pressure transducers, which can become cost-prohibitive for some studies. In some situations, it may be possible to prioritize the need for continuous water-level data, and record water levels in key wells with pressure transducers and data loggers while manually measuring levels in other wells. If the study design calls for single, isolated wells to be instrumented, many manufacturers offer water-level sensing systems that allow the pressure transducer, data logger, power supply and cabling to be installed inside the well bore, thus protecting the entire system from the weather, vandalism, or theft.