Review: Hydraulic head measurements—new technologies, classic pitfalls

Vincent E. A. Post · Jos R. von Asmuth

Abstract The hydraulic head is one of the most important metrics in hydrogeology as it underlies the interpretation of groundwater flow, the quantification of aquifer properties and the calibration of flow models. Heads are determined based on water-level measurements in wells and piezometers. Despite the importance of hydraulic head data, standard textbooks used in groundwater curricula provide relatively little discussion of the appropriate measurement procedures. This paper presents a review of the literature dealing with the determination of hydraulic heads, and aims to provide quantitative guidance on the likely sources of error and when these can be expected to become important. The most common measurement procedures are discussed and the main sources of error are identified, i.e. those related to (1) the measurement instruments, (2) the conversion from pressure to heads, (3) time lag effects, and (4) observation well defects. It is argued that heads should be determined following well-defined guidelines, and that it should become standard practice in hydrogeology to provide quantitative estimates of the measurement error.

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Introduction

Reliable groundwater level measurements are fundamental to all hydrogeological investigations. They are used to establish groundwater flow patterns (Freeze and Cherry 1979), to determine the response of an aquifer to stresses such as pumping or recharge (Von Asmuth et al. 2008; Healy and Cook 2002), to characterize the interactions between subsurface and surface-water bodies (Rosenberry and LaBaugh 2008; Kalbus et al. 2006), and to identify hydrogeologic units (Meyer et al. 2008). Groundwater level measurements are also used to determine aquifer properties such as transmissivity and storativity (Kruseman and De Ridder 1994), and to calibrate groundwater-flow models (Hill and Tiedeman 2007).

The term ‘groundwater level’ is in fact too vague and needs a more precise definition. A more fundamental quantity is the hydraulic head, which is a measure of the mechanical energy per unit weight of water (e.g., Freeze and Cherry 1979). The hydraulic head is a scalar quantity that has a value everywhere within a groundwater body, and in principle, it can be quantified at any point ‘*i*’ in the groundwater system under consideration. Provided that all heads are expressed with respect to the same reference datum and that the groundwater has a uniform density, a comparison of hydraulic head measurements at different observation points provides information on the direction and magnitude of groundwater flow. Groundwater will flow along the hydraulic head gradient (from high to low hydraulic head) at a flow rate given by Darcy’s law. In the literature, the hydraulic head is typically expressed by the following formula:

$$h_\mathrm{i} = z_\mathrm{i} + \frac{P_\mathrm{i}}{\rho_\mathrm{i} g} = z_\mathrm{i} + h_\mathrm{p,i} \tag{1}$$

where h_i is the hydraulic head (L), z_i is the elevation head (L), P_i is the pressure of the groundwater at the measurement point ($\mathrm{ML^{-1}T^{-2}}$), ρ_i is the density of water at the measurement point ($\mathrm{ML^{-3}}$), g is the gravitational acceleration ($\mathrm{LT^{-2}}$) and $h_\mathrm{p,i}$ is the pressure head (L).

Following Lusczynski (1961), the subscript 'i' is used to emphasize that a value is measured at point i. In the case of a non-constant groundwater density distribution, differences in the hydraulic head as defined by Eq. (1) can no longer be used to infer the groundwater flow direction or magnitude, unless additional correction terms are applied (Post et al. 2007; Lusczynski 1961).

Hydraulic head should not be confused or used interchangeably with the water table. The pressure P_i in Eq. (1) is a relative (or gauge) pressure, i.e., it is expressed relative to the atmospheric pressure P_{atm}. The absolute pressure, P_{abs}, is the sum of the atmospheric pressure and the groundwater pressure ($P_{abs}=P_{atm}+P_i$). The water table is defined as the surface at which the absolute pressure equals the atmospheric pressure, i.e., $P_{abs}=P_{atm}$, and $P_i=0$ (Freeze and Cherry 1979), and therefore $h_i=z_i$. In words, the water-table elevation in an unconfined aquifer at a particular location equals the hydraulic head at the depth of the water table. But unless hydrostatic conditions prevail, the hydraulic head below the water table differs from the water-table elevation. Nevertheless, mapping the water-table elevation in an area may be an effective approach to establish the (shallow) groundwater flow pattern, at least approximately.

Although hydraulic heads and water-table elevations may seemingly be the easiest metrics in hydrogeology to obtain, like any physical quantity, their measurement is prone to error and the true values are inherently uncertain. As to whether this uncertainty is acceptable will depend on the nature of the investigation and the purpose of the measurements (Schalla et al. 1992). Failing to appreciate the limitations and imperfections of the instruments and measurement procedures may potentially lead to gross errors in the determination of groundwater flow patterns and magnitudes. For example, Silliman and Mantz (2000) analysed data sets from three sites and found that the error of the head measurements was too large to be able to determine the vertical hydraulic gradient, and that even the direction of the vertical flow could not always be established. In another example, Devlin and McElwee (2007) found that uncertainty about the horizontal hydraulic head gradient due to measurement error in highly permeable aquifers dominated over other sources of uncertainty (like the hydraulic conductivity) in a natural gradient tracer test.

While all 'standard' textbooks on hydrogeology discuss the theoretical principles that underlie the hydraulic head, few of them provide a comprehensive discussion about how it should be measured. Given that hydraulic head measurements form the basis of most, if not all, hydrogeologic studies, this lack of treatment is somewhat surprising, and the present paper aims to fill this gap. Silliman and Mantz (2000) noted a lack of references to estimate the likely magnitude of the errors in the measured water level in a well or piezometer. A comprehensive review of the literature for the purpose of writing the present paper revealed that in fact many publications exist on this subject. The absence perceived by Silliman and Mantz (2000) is likely explained, however, by the fact that they are (1) scattered across various sources, (2) often focus on one specific aspect of the measurement procedure, and are (3) seldom referenced in the mainstream hydrogeological literature. Based on the review that was conducted, the present paper will discuss and attempt to quantify the most common errors associated with the measurement of hydraulic heads with the aim of providing guidance on when certain types of errors may become significant.

Another motivation for this paper was formed by the ever-increasing use of automated pressure recording instruments in groundwater investigations and monitoring programs. The first applications of automated pressure transducers in groundwater studies date back to more than 40 years ago (e.g., Wolff and Olsen 1968; Van Everdingen 1966), but the widespread availability of commercial instruments has led to a surge in the use of these instruments over the past decade. They have enabled cost-effective measurement of hydraulic heads with a high temporal resolution, but the details involved in taking these measurements seem to have only been discussed in no more than about ten publications (Sorensen and Butcher 2011; Price 2009; Cain et al. 2004; Freeman et al. 2004; Hollett et al. 1994; Zarriello 1995; Latkovich 1993; Rosenberry 1990; Ritchey 1986). The findings from these are discussed in the present paper, and complemented by new findings from a study in the Netherlands that investigated the long-term performance of automated pressure transducers in groundwater monitoring networks (Von Asmuth 2010).

This paper will first give an overview of the most common instruments and techniques that are in use to determine hydraulic heads in the field. The errors of the measurement instruments will be discussed, followed by a detailed treatment of the factors that make the water level in a well a potentially unreliable indicator of the groundwater pressure. In what follows, water level or water depth will be used to refer to the vertical position of the air–water interface inside a water-level observation well. The term head will be used as shorthand for hydraulic head, and hydraulic gradient for hydraulic head gradient.

Measurement methods and instruments

Not all studies that involve water level measurements require the measurements to be expressed relative to the same datum (e.g., aquifer tests, or recharge estimation studies based on water-level trends), but when the aim is to establish the groundwater flow based on hydraulic heads from different wells, all heads need to be known with respect to a fixed reference elevation. For regional investigations, this is usually the national datum level, but for local studies, an arbitrary local datum level may be chosen. The most common procedure to determine the hydraulic head is then to measure (1) the elevation of the rim of an observation well with respect to the chosen reference datum and (2) the water depth within the well.

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This measurement procedure requires several instruments: the observation well itself, and instruments to measure (1) and (2).

Piezometers and observation wells

An observation well that is specially designed and constructed to measure the hydraulic head at a specific point in the subsurface is called a piezometer. The basic premise underlying the measurement of hydraulic head using a piezometer is that the height of the water column is a measure for the pressure of the groundwater P_i at the piezometer location and depth z_i, and that by measuring the water level the hydraulic head can therefore be known. Figure 1 shows a schematic depiction of a piezometer, and graphically illustrates the different head terms from Eq. (1). The elevation head z_i is the elevation of the measurement point with respect to a reference datum. Because piezometers have a certain screen length, heads measured with them are never strictly point measurements, but represent some integrated value along the well screen. In practice, it is customary to define z_i as the elevation of the midpoint between the top and bottom of the screen.

Reference works on geotechnical engineering describe a variety of piezometer types and designs (e.g., Lancellotta 2008; Dunnicliff 1993). The discussion here, however, will focus on the most widespread piezometer type to measure the head in aquifers, which is the standpipe piezometer (Lancellotta 2008), simply referred to as piezometer in the hydrogeologic literature. It consists of a hollow tube (made of PVC, stainless steel or HDPE), with an inner diameter typically between 2 and 6 cm, that is perforated near the bottom end (Fig. 1). The inner diameter is preferably kept as small as possible, to minimize the volume of water that has to exchange

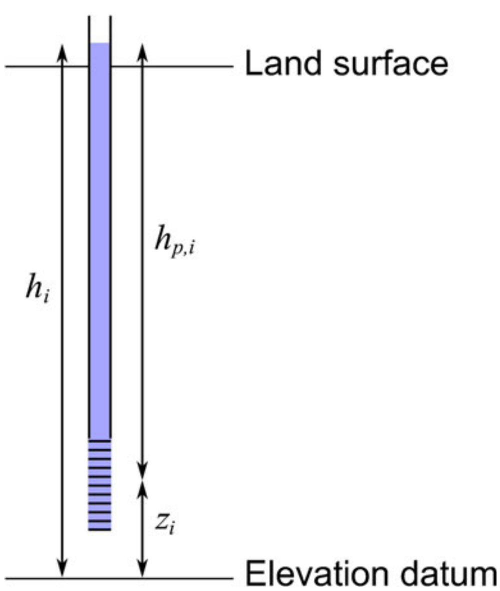

Fig. 1 Schematic representation of a piezometer and the terms in Eq. (1)

between the piezometer and the surrounding strata. Small diameters, on the other hand, may prohibit the access of other equipment like underwater pumps, or downhole probes and cameras, and this needs to be considered during the design stage of a project if the piezometer is to have various measurement objectives.

The screened section typically consists of a tube of the same material as the standpipe in which horizontal or vertical slots are cut. Slot openings are typically 0.1–1 mm wide (Nielsen and Schalla 1991). To prevent the entry of small diameter particles like silt from the surrounding rock material, a filter pack (or gravel pack) or a gauze (or both) is typically installed around the well screen. When the filter pack consists of granular material with a permeability much higher than the adjacent formation, it effectively works to extend the screen diameter to the borehole diameter (Schwartz and Zhang 2003). Consequently, more water needs to flow between the formation and the borehole for the piezometer to record the pressure of the groundwater outside the borehole. If a borehole intersects multiple aquifers separated from each other by confining layers, care must be taken to seal off any connection between the aquifers by back-filling the annular space between the monitoring well and the borehole wall with low-permeability material such as bentonite. Proper borehole construction and well development require specialist technical skills and a complete discussion of all aspects and details is beyond the scope of the present article. Readers are referred to textbooks such as Nielsen (1991) and Driscoll (1986) for a comprehensive discussion on the topic of well construction and design.

The slotted section or screen is typically 0.2–3 m long, but this may vary. Ideally, the screen length should be kept as short as possible. The optimal screen length depends on a number of considerations. For example, if the permeability of the strata in which the screen is installed is low, then a relatively long screen length may be preferred to reduce the equilibration time between the water column in the piezometer and the groundwater. For investigations at the local scale with high vertical head gradients, however, the screen's size should be kept as small as possible in order to resolve vertical head variations as accurately as possible.

When the water-table elevation is sought after, a so-called water-table observation well must be used (Schwartz and Zhang 2003). This type of observation well is screened across the water table and, provided that the water in the well is stagnant, measures the top of the saturated zone. Large-diameter open wells that are in use in many areas for agricultural or domestic water supply, can serve a purpose as water-table observation wells. Care must be taken though that the level in the well actually represents the water table outside the well and that it is not affected by recent pumping.

Water-level measurements

The two most-widely used ways to measure the water level in a piezometer or well are by (1) lowering a

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measurement tape to the water surface or (2) suspending a pressure sensor in the water column. The parameters that need to be known to determine the hydraulic head from the measured quantities are schematically depicted for both cases in Fig. 2. With these measurements, it is the hydraulic head that is determined, and nothing can be said about the pressure head and elevation head unless an accurate measurement of the depth to the top and bottom of the well screen is available. This may seem like a trivial point, but it can become a critical issue if head corrections to account for density effects are required (Post et al. 2007).

At present, the most favoured instrument for manually measuring the water depth is the electric probe attached to a graduated measurement tape (Dalton et al. 2006), which is often referred to as a water-level meter, a dipmeter or a dipper (Brassington 2007). The probe houses two electrodes and an electrical circuit is closed when the probe is immersed into the water inside the well, which activates a light or a buzzer at the surface. The non-electric variant is a so-called plopper or popper, which consists of a metal (e.g., brass) cylinder with an open end at the bottom that is attached to a graduated measurement tape. When the open bottom hits the water in the well, a clearly audible plopping noise is heard. The depth to the water level can be found by moving the tape up and down in short intervals.

Although, due to their ease-of-use, electronic water-level meters have become the instrument of choice in most water-level surveys, the wetted chalk tape method is identified in the literature as the most accurate method to measure the water depth (Dalton et al. 2006; Sweet et al. 1990). With this method, the bottom part of the tape is coated with chalk and the tape is lowered into the well until the chalked portion of the tape is partially submerged. The water depth is the difference between the reading of the tape at the well casing and the reading of the submerged distance.

Since the 1990s, electronic pressure transducers have become mainstream instruments to measure water levels. Their sophisticated technology may suggest that these are superior to tape measurements but this is certainly not true when it comes to accuracy and reliability. Various technologies exist for determining pressures (Freeman et al. 2004), but most pressure transducers used in groundwater investigations measure the strain that is generated by a force on a surface by recording the electrical resistance of a strain gauge. The surface is typically formed by a silicon diaphragm that deflects as pressure is applied. When submerged in a water column, water sits on one side of the diaphragm, while in a chamber on the other side of the diaphragm, a lower pressure exists. Another type of pressure gauge, which is particularly used in geotechnical investigations, is the vibrating-wire pressure transducer. These work based on the principle that the resonant frequency of a vibrating wire changes when the wire's tension is altered due a change of the pressure on a diaphragm. Details of this technique can be found in Zarriello (1995).

A distinction is made between vented and non-vented transducers. The chamber of a *non-vented* pressure transducer is sealed and in this case, the recorded pressure is the absolute pressure, P_{abs}. The chamber of a *vented* pressure transducer is open to the atmosphere and the recorded pressure is a gauge pressure. This gauge pressure is the pressure P_{i} in Eq. (1), which is expressed relative to

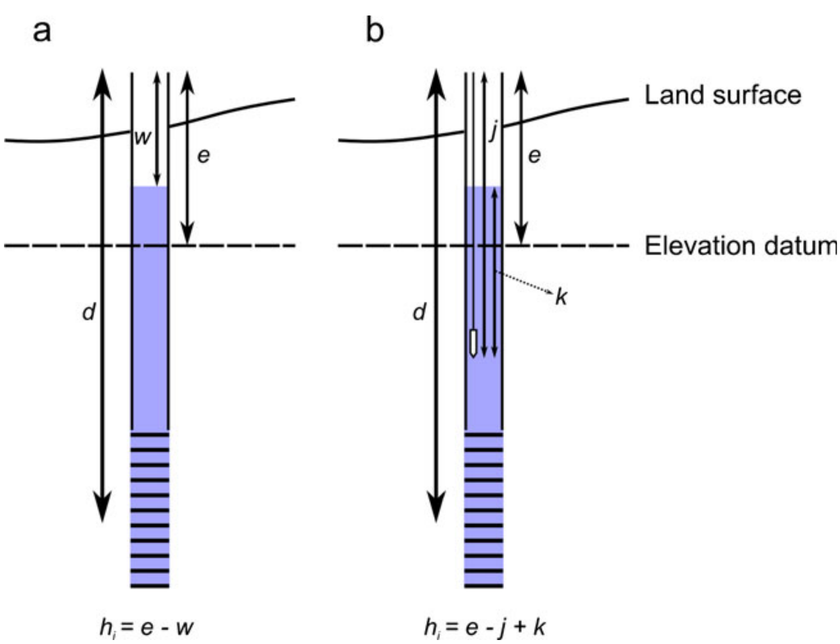

Fig. 2 Schematic representation of the measurements involved in determining hydraulic head. **a** The height of the rim of the well with respect to the elevation datum is known. **b** The height of the rim of the well with respect to the elevation datum is known and water level is measured with a pressure sensor. d = well length (measured between the top of the casing and the centre of the well screen), w = depth of water level below the rim of the well, e = the height of the well rim above elevation datum, j = the depth of the pressure sensor below the well rim, and k = the height of the water column above the pressure sensor

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the local atmospheric pressure, P_{atm}. Care must be taken with vented pressure transducers that have a hollow tube that runs down the well to establish a connection with the atmosphere above. Condensation may occur in this venting tube and a desiccation agent (like silica beads) is usually needed to prevent this from occurring.

One notable advantage of electronic pressure transducers is that the measurement process can be automated if they are connected to a data logger. Although automated water-level recording systems such as float-operated chart recorders, have been used for decades (Dalton et al. 2006), modern instruments and computer software provide a cost-effective means of collecting time-series data in unprecedented quantities and temporal resolution. Telemetric systems exist that eliminate the need for a person to collect the recorded data in the field. Caution is required here, however, because as will be discussed later on, regular manual measurements remain essential to detect instrument malfunctioning and drift.

Various other methods to determine the water level in wells are described in the literature (Cunningham and Schalk 2011; Dalton et al. 2006; Sweet et al. 1990; Driscoll 1986), but will not be discussed here, except for the submerged air-line method and the measurement of artesian heads, which both require determining the pressure using a pressure gauge. The air-line method remains in use for determining the water level in pumped wells where the use of a measurement tape or a pressure transducer is not possible. This method involves inserting a pipe to a known depth into the well so that its lower end is submerged. Air is pumped into the pipe and the increasing air pressure is monitored until it stabilises at the value where it expels all the water from the pipe. The pressure is then converted into a water level by dividing it by an appropriate value of the specific weight of water inside the well (Cunningham and Schalk 2011).

In artesian groundwater systems, the pressure at the well screen is so high that the water level in the well rises to a height that is greater than the land surface or the well rim. In order to be able to measure the head in such wells, the top of the well either needs to be extended, or the head is derived from a shut-in test, during which the flow of water through the well is stopped and the pressure at the land surface is recorded using a pressure gauge (Brassington 2007). The pressure of the groundwater at the well screen is the sum of the recorded pressure and the pressure due to the water column between the pressure gauge and the well screen. In this case, the hydraulic head is found by converting the pressure to pressure head and adding this to the elevation head (cf. Eq. 1).

Measurement errors

The error of a head measurement is the degree to which the measured value differs from the true head value. In practice, multiple factors contribute to the measurement error and these may be more or less difficult to quantify separately. The accuracy of a measuring device, i.e., the degree to which it records the true value of the quantity being measured, can be quantified in principle. The precision of head measurements, i.e., the closeness of agreement between independent head measurements, obtained by applying a stated measurement procedure several times under prescribed conditions (WMO 2008), is already harder to quantify. This is because the precision depends on a number of factors such as the instrument specifications (e.g., the number of markings on a measurement tape that determine the smallest possible reading) and the skill of the operator, but also because the conditions under which head measurements are conducted in the field are difficult to control, and are likely to differ between one measurement and the other (Atwood and Lamb 1987). In the following discussion a distinction is made between four types of errors: those due to the (1) measurement instrument, (2) conversion of pressures to water levels, (3) time lag effects, and (4) defects of the piezometer or observation well.

Instrument errors

The accuracy of hydraulic head measurements relative to a reference datum is determined to a large extent by the accuracy to which the elevation of the well rim with respect to that reference datum can be measured (Schalla et al. 1992). The most accurate results are obtained using a surveyor's level. With this method, the accuracy mainly depends on the total length of the survey line and the number of instrument setups (Schalla et al. 1992; Kennedy 1990). The elevation determined in a carefully conducted land survey can be found to within one centimetre (Brassington 2007). Alternatively, well elevation data may be obtained using global positioning system (GPS) readings, contour lines on topographic maps, remotely sensed land-surface elevation data or barometric altimeters. With the exception of certain GPS methods such as real time kinematic GPS, which can attain a vertical accuracy that rivals that of a land survey (Lambiel and Delaloye 2004), the accuracy of each of these methods is typically in the order of meters. The use of such data beyond anything other than an initial, general reconnaissance study is questionable, and any quantitative analysis based on them should be avoided.

A potential source of error can be introduced by an uneven well rim height, particularly for large diameter wells. This source of error can be eliminated by ensuring that the rim is level during the construction of the observation well or piezometer. If the inclusion of wells with an uneven rim can not be avoided, care must be taken that the rim elevation and water-level measurements are consistently taken at the same point. For this reason, marking of the survey point on the well rim should be standard practice.

The accuracy of measurement-tape based methods is better than a centimetre for most conditions, although tape wear, kinks and non-vertical suspension may negatively impact this (Sweet et al. 1990). The accuracy of the tape itself is also an important factor. Commercially available tapes are available in different degrees of accuracy, and these are specified in standards such as the NIST 44 (Butcher et al. 2012) or the European accuracy classes I, II and III (Organisation Internationale de Métrologie Légale 2007). Tapes of dipmeters that are not manufactured to any standard can be out by more than 5 cm over 30 m (J. Sorensen, JPR, British Geological Survey, personal communication, 2012). Similar findings were reported by Plazak (1994). Regular calibration of measurement tapes against one and the same tape of the highest accuracy class should therefore be standard practice.

Electronic water-level meters may not work optimally under all circumstances, e.g., in water of very low electrical conductivity, in the presence of non-aqueous fluids, or in salt water where water films can form bridges between the co-axial elements of the sensing tip and thereby cause erroneous readings (Baird et al. 1998). Bias may be introduced when the same measurement is made by different observers: Sweet et al. (1990) found that the precision of water-level measurement due to the skill of the observer varies between 0.21 and 0.34 %.

Under certain conditions, thermal expansion and stretch due to the mass of the tape and its plumb weight can become significant (Garber and Koopman 1968). Measurement tapes are usually calibrated at 20 °C and the correction of the tape length due to the temperature deviating from this value can be calculated from:

$$\frac{\Delta L_{\mathrm{T}}}{L_{\mathrm{m}}} = C_{\mathrm{T}} \cdot (T - T_{\mathrm{ref}}) \tag{2}$$

where ΔL_{T} is the thermal correction (L), L_{m} is the measured depth (L), C_{T} is the coefficient of linear thermal expansion (°C^{-1}), T is the temperature (°C) and T_{ref} is the reference temperature (°C). Figure 3 shows the value of ΔL_{T} as a function of temperature and L_{m} for $C_{\mathrm{T}}=11\times 10^{-6}$/°C, which is the coefficient of linear thermal expansion for steel tape as well as the steel wires used in many commercially available electronic water-level meters. It can be inferred that the effect of thermal expansion can become significant in deep wells and at high temperatures. However, even for shallower water levels, quantifiable errors may already be introduced if the same measurement tape is deployed in winter or summer. What is also interesting to note is that the coefficients of linear thermal expansion differ between the metal supporting wires and the coating that houses the wires and onto which the markings are printed. The difference may be more than a factor of 10, with the coating stretching more than the steel wire. This may affect the precision of the measurement tape in a way that is hard to predict.

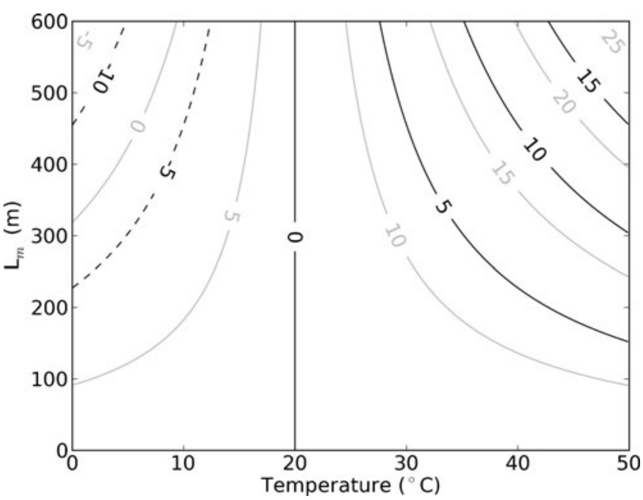

Fig. 3 Contour plot of the stretch of a steel tape as a function of temperature and measured water-level depth (L_{m}) due to (1) thermal expansion according to Eq. (2) (*solid and dashed black lines*) and (2) both thermal expansion and tension according to Eqs. (2) and (3) (*grey lines*). Contoured values represent the values that need to be subtracted from the measured water-level depth to approximate the true water-level depth and are given in cm

Garber and Koopman (1968) also provided a correction formula to account for the stretch caused by the measurement tape's own weight and the plumb weight attached to it:

$$\frac{\Delta L_{\mathrm{W}}}{L'_{\mathrm{m}}} = C_{\mathrm{W}} \cdot \left(W L'_{\mathrm{m}} + W_P \right) \tag{3}$$

where ΔL_{W} is the weight stretch correction (L), $L'_{\mathrm{m}}=L_{\mathrm{m}} - \Delta L_{\mathrm{T}}$ (L), C_{W} is the coefficient of stretch (M^{-1}), W is the tape mass per unit length of tape (ML^{-1}) and W_{p} is the mass of the plumb weight attached to the tape (M). Figure 3 shows the values of ($\Delta L_{\mathrm{T}} + \Delta L_{\mathrm{W}}$) as a function of temperature and L_{m}. For temperatures above T_{ref} (i.e., 20 °C), the stretch due to the weight tends to increase the required correction, but for temperatures below T_{ref}, the stretch tends to lower the required correction as it counteracts the thermal contraction of the steel.

The accuracy of different pressure transducers varies between models and manufacturers. It is generally expressed as a percentage of the full scale (FS) measuring range. For example, 0.1 % FS for a sensor with a range of 10 m means that the values are 'accurate to within 1 cm'. An increase in the measurement range will result in a loss of accuracy, which should be a consideration when choosing the appropriate instrument for a given application. An important consideration is also the choice between a vented and a non-vented pressure transducer. As the water pressure relative to the atmospheric pressure is normally the variable that is sought after, rather than the absolute pressure, values recorded by non-vented pressure transducers have to be compensated for atmospheric pressure, which is independently measured. The accuracy will thereby decrease as the variance of the errors of both instruments accumulates.

Pressure transducers are prone to various types of errors (Von Asmuth 2010), including instrument drift (Sorensen and Butcher 2011; Rosenberry 1990) and sensitivity to temperature variations, which may or may not be adequately compensated for (McLaughlin and Cohen 2011; Cain et al. 2004). Such errors are especially clear (and may be corrected) when air pressure measurements are compared to data from more accurate (digital)

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barometers (De Meij and von Asmuth 2011), or when submerged pressure sensors become uncovered as the water level in a piezometer drops. Figure 4 shows an example time series of pressure data, which illustrates the main types of errors. The water level dropped below the bottom of the observation well for most of the time, during which the sensor should give a reading of 0. Due to the drift of the instrument, there is a clear deviation from zero that increases with time, and the drift is affected by seasonal temperature changes (Fig. 4c). There is also a hysteresis effect, where the transducer responds differently to increases in pressure than to decreases in pressure, which sometimes causes negative readings, which are, of course, erroneous (Fig. 4b). While the data in Fig. 4 present the different sorts of error, their magnitude is relatively small, but experience with commercially available instruments has shown that errors may amount to several centimeters or even decimeters in other cases (Sorensen and Butcher 2011; Von Asmuth 2010). Therefore, and as stated earlier, regular manual water-level measurements should be standard practice to determine any drift of the pressure transducer, and provide a means to correct for this effect.

Errors may also be introduced when the internal clocks of the loggers are inaccurate and different, i.e., when the recorded water and air pressures, or the pressures recorded in different wells, are asynchronous. Deviations of up to 30 min/year are not uncommon for commercially available water-level loggers. This source of error can easily go unnoted, but may introduce significant interpretation flaws when rapid pressure changes with time need to be resolved. A final potential source of error associated with the use of pressure transducers is related to the length of the suspension wire. As with measurement tapes, it is subject to expansion due to thermal effects and strain, and its length must be measured with a calibrated measurement tape under the same stretch as in the well, which may be non-trivial for very long wires. Therefore, the length of the suspension wire is best deduced from a manual measurement of the water level, taken at the same

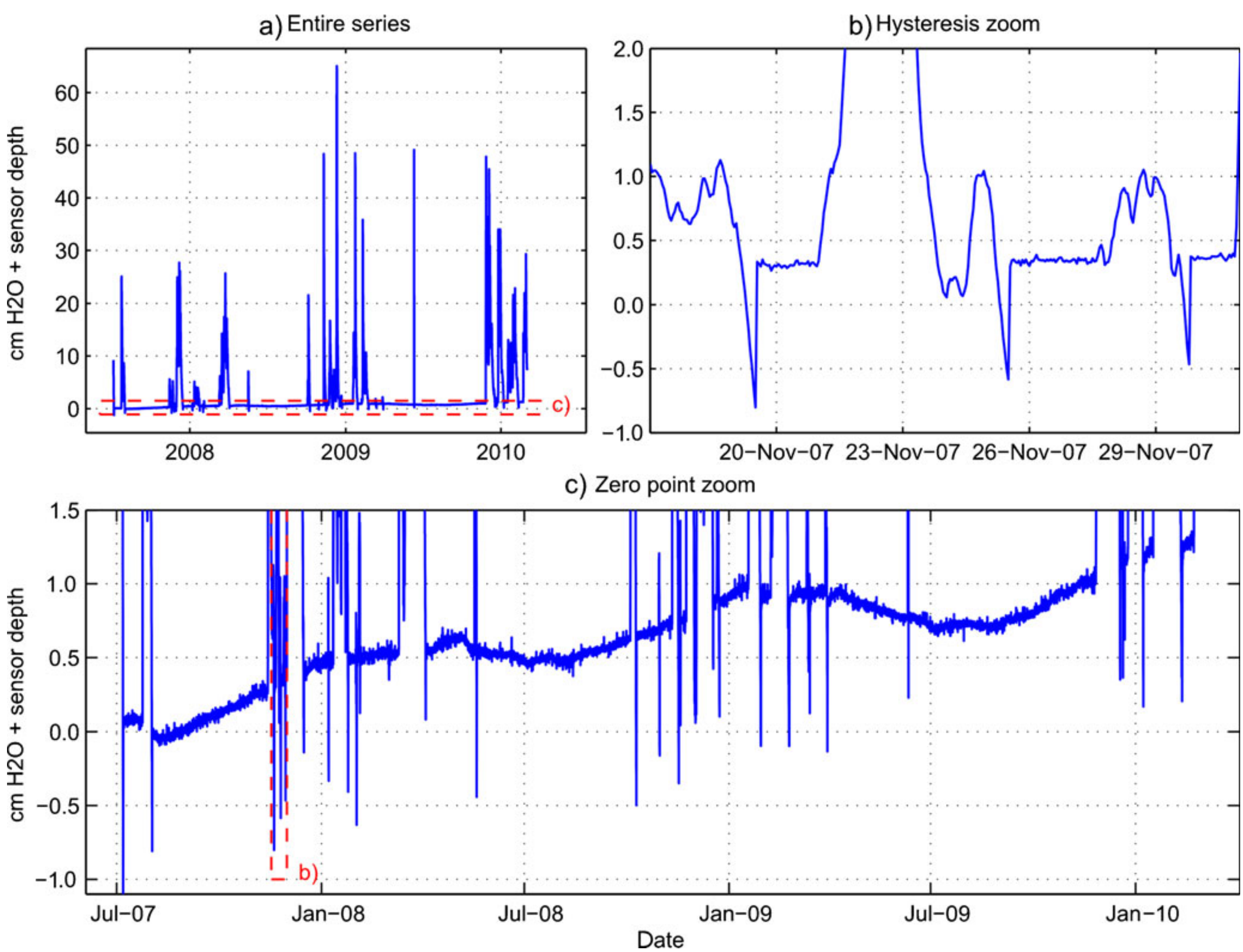

Fig. 4 Different zooms on a groundwater-level series collected with a vented pressure transducer that is periodically uncovered, showing several types of pressure sensor related errors. **a** A plot of the entire series, showing the axes limits in **c** as a *dashed box*; **b** zoom of three events where the water level drops below the pressure sensor, showing errors due to hysteresis (resulting in negative values when the levels are decreasing); **c** zoom on the zero point, showing temperature sensitivity (the seasonal pattern in the zero point), drift (the gradual increase of the zero point with time), noise (the random variation around the zero point) and hysteresis

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time as the first measurement by the pressure transducer in the observation well.

Pressure-head conversion

The pressure head $h_{p,i}$ that appears in Eq. (1) expresses the pressure of the groundwater at the measurement point as the length of a water column of density ρ_i, that is:

$$h_{p,i} = \frac{P_i}{\rho_i g} \tag{4}$$

For most practical applications, $h_{p,i}$ is thought to be indicated by the length of the water column in the piezometer (cf. Fig. 1). Strictly, however, this is never the case because for various reasons the density of the water inside piezometers will always vary with depth and deviate from ρ_i. If the water in the standpipe of a piezometer is at rest, P_i and density are related according to:

$$P_i = \int_{z_i}^{z_i + h'_{p,i}} \rho_w(z) g dz \tag{5}$$

where $\rho_w(z)$ (ML^{-3}) is a function that describes the variation of the density of the water inside the piezometer with the vertical coordinate z, and $h'_{p,i}$ is the length of the water column inside the piezometer. The average density of the water column inside the piezometer ρ_a is:

$$\rho_a = \frac{\int_{z_i}^{z_i + h'_{p,i}} \rho_w(z) dz}{h'_{p,i}} \tag{6}$$

which can be inserted into Eq. (5) to give, after rearranging:

$$h'_{p,i} = \frac{P_i}{\rho_a g} \tag{7}$$

By comparing Eqs. (4) and (7), it can be seen that the water column length in a piezometer $h'_{p,i}$ only indicates the pressure head $h_{p,i}$ if $\rho_a = \rho_i$. Figure 5 illustrates the potential degree of misinterpretation that may result when this is not the case, such as when a density stratification develops in a piezometer as the water temperature equilibrates with that of the subsurface. In this example, a 500-m-deep aquifer contains hydrostatic freshwater, and the water table is at the land surface where z=0. Therefore the head h_i=0 everywhere within the aquifer. The left panel shows the temperature T and density ρ of

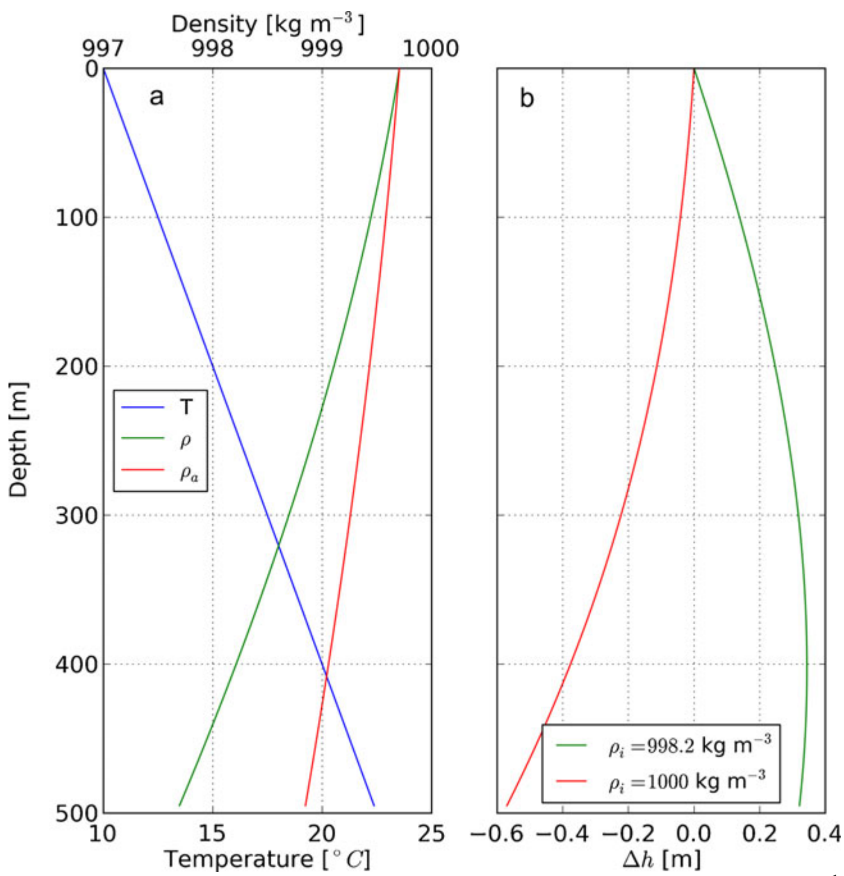

Fig. 5 **a** Graph showing the change with depth of (1) the temperature T for a geothermal gradient of 25 °C km^{-1} and a surface temperature of 10 °C, (2) the water density (ρ) at the prevailing value of T and (3) the average water density (ρ_a) between z=0 and $z = z_i$. **b** Head that would be observed in a piezometer measuring at a depth indicated by the vertical axis if the prevailing pressure at that depth were to be expressed as a column of water with a density of ρ_i=998.2 kgm^{-3} or ρ_i=1,000 kgm^{-3}

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groundwater with depth. Density variations are induced by changes in temperature only, and a typical geothermal gradient of 25 °C km^{-1} (Phillips 2009) was assumed. The left panel also shows the function $\rho_a(z)$ that represents the average groundwater density between $z=0$ and $z = z_i$. The right panel shows the water level in a piezometer if it were to have a vertically constant density of ρ_i=1,000 kg m^{-3} or ρ_i=998.2 kg m^{-3}. Although the effect is non-linear, this graph shows that the water column height $h'_{p,i}$ gives an erroneous indication of the pressure head $h_{p,i}$ by approximately 1 mm/m of water column.

The practical implication that follows from this example is that piezometers are imperfect measurement instruments, and do not indicate the hydraulic head in a way that is consistent with its definition according to Eq. (1), because the density of the water columns inside them cannot be controlled and is generally unknown. A simple analysis like the one presented in the preceding can be used to assess under what conditions temperature effects become important. Thompson (1976) noted the problem of accurately determining artesian pressures for wells in the Great Artesian Basin in Australia due to the temperature-related density effects. In order to be able to assess or correct for the error induced by temperature-related density changes, Winograd (1970) recommended that in deep wells, head measurements are to be accompanied by a thermal survey. However, when small head differences are the object of investigation, it is recommendable to assess the potential magnitude of the effect for shallow observations as well, because density variations can also occur due to seasonal temperature variations in the upper 10–20 m of the subsurface (Fig. 6). Subsurface temperatures may range between 0 and 25 °C in a temperate climate (Anderson 2005) and the corresponding range in density of freshwater is 1,000 to 997 kg m^{-3}, which means that failing to account for this variation may result in an error of up to 3 mm/m of water column.

Even if the vertical temperature profile of a well is known, uncertainty remains about the density stratification within wells, as density variations may further stem from salinity variations, the presence of non-aqueous liquids or dissolved gases (Spane 1999) and the increase of water pressure with depth (Adams and Bachu 2002). An example of a vertical density stratification that has developed inside a well due to salinity variations is shown in Fig. 7. One approach to overcome this problem is to remove the standing water in the piezometer before the head measurement is taken (Van der Eem 1992), but this may not always be feasible and care must be taken that sufficient time has elapsed for the water level in the well to re-equilibrate with the ambient pressure outside the piezometers (over which a temperature profile will also re-establish). Another remedy is to measure the pressure at the depth of the well screen directly (Winograd 1970), but if the well is deep or inaccessible, this may be impossible, or possible only at the expense of a less accurate measurement.

The same difficulties that may arise when relating P_i to the pressure head $h_{p,i}$ also apply to the use of pressure transducers and air-line methods to determine the water level inside piezometers, as the measured pressure has to

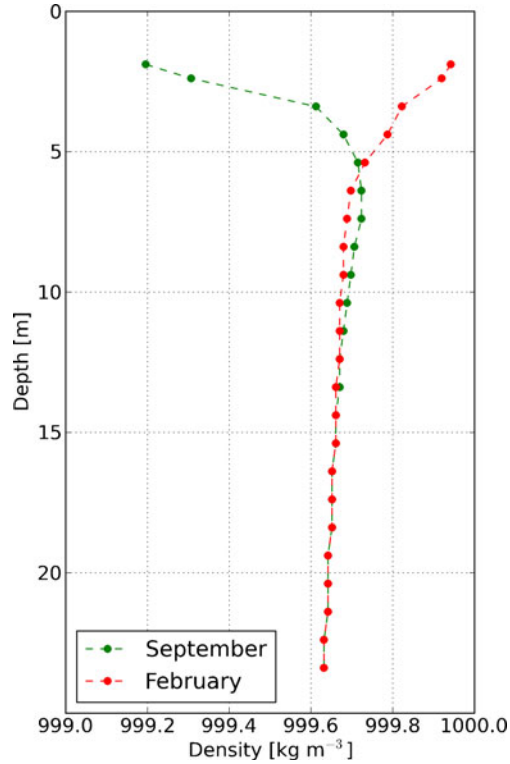

Fig. 6 Density variations inside a piezometer near the city of Amsterdam in the Netherlands due to seasonally variable temperature changes. Densities were calculated based on the prevalent electrical conductivity as suggested by Post (2011) for a variable temperature as measured using a down-hole thermistor probe in September and February 2003

be expressed as the height of a column of water. Different manufacturers use different assumptions about, and default values of, the parameters ρ_w and g and the observer should always ascertain that the conversion is appropriate and does not introduce systematic errors. For example, g is often taken to be equal to the standard gravity, i.e., g=9.80665 m s^{-2}, but may vary between 9.78 and 9.83 m s^{-2} across the globe (Telford et al. 1990). For a constant density, the systematic error that may be introduced by using the standard gravity instead of the local value could be as high as 2 mm/m of water column. The errors can be minimized by positioning the pressure transducer just below the minimum water level in the well and not at excessive depth. However, as water levels vary with time, the height of the water column above the pressure sensor will vary, and thus also the potential error. Some manufacturers offer the option of temperature-dependent density corrections, but this may suggest an accuracy that is unwarranted as the temperature measurement used to correct the density pertains only to the point in the well where the sensor is measuring, and does not represent the integrated average density of the entire water column above it.

A source of error related to the use of non-vented pressure transducers resides in the fact that it is common practice to measure the air pressure variations at a certain distance away from the piezometer in which the head is

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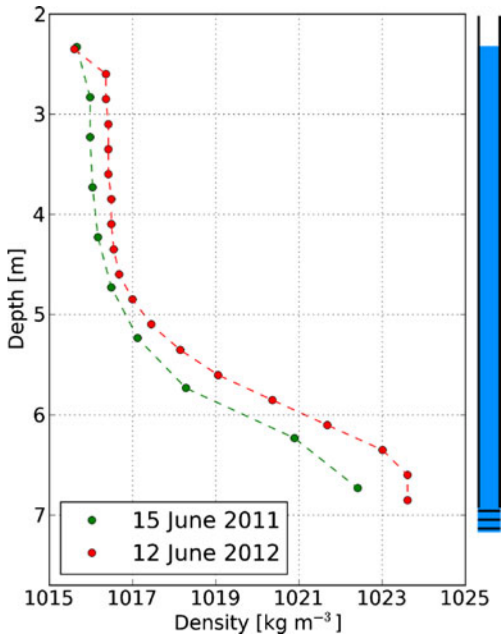

Fig. 7 Density variations due to salinity variations in a shallow piezometer intersecting the freshwater–saltwater transition zone in a shallow sandy coastal aquifer. A clear stratification can be observed across the 5-m water column, which persists for years despite the flow in the piezometer induced by the semi-diurnal tide, which results in a fluctuation of the water level in the piezometer of ~50 cm. Densities were calculated based on the electrical conductivity as suggested by Post (2011) for a constant temperature of 16 °C. The position of the screened section of the piezometer is indicated by the schematic diagram to the right of the graph

measured. It is customary, for example, to equip a number of nearby piezometers with water-level loggers and use only one logger to measure the air pressure that will be used to correct the pressure measurements made in all piezometers. Local differences in air pressure thus translate into errors in the inferred hydraulic heads. Table 1 quantifies the potential magnitude of this effect by comparing the air pressures recorded at five meteorologic stations to one other station. It can be seen that, in general, and as expected, the difference increases with the distance between the stations. The maximum deviations between the hourly values may be in the order of 2–3 cm of water column over a distance of 35 km, but increase to 17 cm over a distance of 278 km.

As the atmospheric air pressure importantly varies with height, the vertical separation between the atmospheric pressure transducer and the submerged pressure transducer may contribute to a significant pressure difference that must be taken into account in converting the pressures to heads. This is the case in areas with topographic relief, but also in wells with a deep water table where the atmospheric pressure is measured at the surface. To assess the magnitude of this effect, the average atmospheric pressure P_{atm} at 20 °C can be calculated by (Allen et al. 1998):

$$P_{atm} = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \quad (8)$$

where P_{atm} is the atmospheric pressure (kPa), and z is the elevation above sea level (m). For example, if the land surface is 100 m above sea level and the water level in the observation well is 50 m lower, the air column between the water level and the land surface corresponds to a water height of already ~6 cm.

Time lag effects

One important reason why the water column in an observation well may not correctly indicate the pressure of the groundwater at the well screen is that the water level in the well always needs some time to equilibrate with the prevailing groundwater pressure. The factors that determine the response time of a piezometer, besides the transmissivity and storativity of the aquifer, include the volume of the well, its screen length and the local permeability of the strata adjacent to the well screen. Response times are in the order of seconds to minutes in permeable formations and may increase to days or even more for impermeable strata such as silt, peat and clay (Hvorslev 1951). For certain investigations, this time lag should be considered, for example when interpreting pumping test data (Black and Kipp 1977) or rapidly fluctuating head variations. Turner (1998) recommended that if the oscillations have a frequency of 1 min or less such as those caused by wave run-up on beaches, piezometers should be avoided altogether, and pressure transducers should be buried into the sediment. It should also be realised that the submersion of a measurement instrument like a pressure transducer may cause the water level inside a piezometer to rise by a few centimetres and a significant amount of time may be required before the piezometer re-equilibrates with the pressure at the well screen.

Table 1 Differences in atmospheric pressure between several stations of the Royal Dutch Meteorologic Institute and the station in Hoorn, in the Netherlands (in cm water column), corrected for differences in surface elevation (de Meij and von Asmuth 2011)

	Leeuwarden	Lelystad	Deelen	Volkel	Eindhoven	Maastricht
Distance (km)	35	112	153	196	218	278
Pressure differences:						
Average	0.2	0.6	0.8	1.0	1.1	1.4
Average absolute	0.4	1.2	1.7	2.1	2.3	2.9
Deviation (2σ)	±0.9	±2.8	±4.0	±5.0	±5.5	±6.9
Minimum	−2.2	−4.2	−5.8	−12	−7.5	−9.4
Maximum	3.1	8.2	10.2	12.6	13.9	17.1

The values are based on a comparison of hourly pressure measurements over a period of 10 years

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Standpipe piezometers commonly show a response in water level related to changes in atmospheric pressure. The reason for this is that the piezometer is in direct contact with the atmosphere but the water in the aquifer, even if it is unconfined, is not. Therefore, the water level in the well will respond immediately to a change in atmospheric pressure, whereas the head in the aquifer will show a delayed and possibly dampened response. The delay of the response to atmospheric pressure itself may be derived from the observed groundwater head fluctuations using time series analysis (Von Asmuth et al. 2008). The degree of response is expressed by the barometric efficiency (Freeze and Cherry 1979):

$$\beta = -\frac{\rho_{\mathrm{w}} g \Delta h}{\Delta P_{\mathrm{atm}}} \quad (9)$$

in which Δh (L) is the change in the water level in the observation well over an arbitrary time interval and ΔP_{atm} ($\mathrm{ML^{-1}T^{-2}}$) is the change in atmospheric pressure over the same time interval. The causes for the occurrence of barometric effects differ between confined and unconfined aquifers. In a confined aquifer, the change in atmospheric pressure is borne partly by the aquifer grain skeleton and partly by the pore water. Because part of the pressure change is accommodated by a change in effective stress of the aquifer skeleton, the change in pore water pressure is less than the atmospheric pressure change. In unconfined aquifers, there may be a significant delay in the arrival of atmospheric pressure changes at the water table. If the unsaturated zone has a low permeability to air, or if the water table is very deep, there may be a considerable time lag between the change in atmospheric pressure and the moment it is experienced by the water table (Price 2009). The change in volume of entrapped air in the saturated or unsaturated zone has also been suggested to play a role (Freeze and Cherry 1979).

Regardless of which process causes barometric pressure effects, they represent artefacts that make the water level in an observation well form an erroneous indication of the hydraulic head within the aquifer. Procedures for correcting water-level measurements in wells for barometric effects are discussed in detail in Spane (2002) and Rasmussen and Crawford (1997), and Hubbell et al. (2004) present the design of an observation well and pressure transducer configuration that minimises barometric pressure effects on measured water levels.

Piezometers and observation well defects

Drilled production or pumping wells are often used as a surrogate for piezometers but suffer from drawbacks such as large diameters, long screen lengths and access issues due to the presence of pumps and electric wiring. It is well-known that the suitability of such wells should always be critically evaluated and details about their construction must be reported. A well screen that intersects multiple aquifers of different permeability will have a water level that is affected by the head in each layer in proportion to the transmissivity of each layer (Sokol 1963). A risk with long well screens is that the well may induce vertical flow. Several documented cases have been reported in the literature (e.g., Elci et al. 2001). Besides potential harmful effects such as aquifer cross-contamination, induced vertical flow renders a well useless as an accurate measurement device for water-level measurements, as the flow of water inside the well will influence the water level.

Even carefully constructed piezometers may at some point lose their value as a reliable measurement instrument. Potential reasons include the development of leaks due to faulty joints, cracking or corrosion of the casing (Van der Kamp and Keller 1993), or clogging of the well screen. The latter may be impacted by factors such as drilling and well construction (i.e., admixture of bentonite in the filter pack), mineral precipitation (e.g., iron hydroxides) and bio-clogging. In pumping wells, clogging is known to significantly affect water production rates (e.g, Van Beek 2010) and is likely to negatively impact the accuracy of the well as an instrument. Well screens may further get clogged by organic or sediment fines that settle from the water column in the well after they have penetrated through the well screen, leaky pipes or through the well opening at the land surface.

Concluding remarks

From the discussion presented in the preceding, it is clear that the measurement of the hydraulic head is not as trivial as simply lowering a measurement tape down to the water level in a well. Even when standard operating procedures are carefully followed in order to achieve maximum accuracy and precision, there may be significant errors. While the determination of the well rim elevation with respect to a common reference datum may introduce some error, the largest errors are related to the measurement of the water depth, and to the fact that the observation well may not be a representative indicator of the groundwater pressure in the adjacent formation. In practice, data processing errors (e.g., typing errors, mixing up of well screens in multi-level piezometers) introduce even larger errors in the archived data, but as these are not due to the actual measurement process, these have not been discussed in this paper.

Operator skill, proper instrument use and calibration are key factors in determining the quality of the measurements. The standard methods for well installation and the measurement of water levels in wells are outlined in standards such as those from the International Organization for Standardization (ISO 2005; Stölben and Eitner 2004), or organisation-specific standards like the technical procedures of the U.S. Geological Survey (Cunningham and Schalk 2011). It is the impression of the authors, however, that, in many investigations, the measurements are not conducted in accordance with such standards and that the quality of the data thus collected can not be assured. Moreover, while standards aim to

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ensure proper piezometer installation and reliable water-level measurement, they provide little guidance on the possible sources of error, such as temperature-induced density effects, that introduce uncertainty in the conversion of the measured water levels or pressures to hydraulic head values. Consequently, the potential errors due to these effects may remain unnoticed and unquantified, and there is a need to establish a protocol for the minimum data requirements for converting pressures and water levels into hydraulic heads. Such additional metadata could include the electrical conductivity and temperature (as proxies for the water density) in the well.

In addition, the archiving requirements of head data should be developed, so that the original measurement values are stored, rather than the final derived head value. This is particularly true for heads based on pressure measurements that require assumptions about the specific weight of the water column to convert between pressure and water column height. These assumptions vary between different manufacturers of pressure transducers, and may become critical in studies when a high accuracy is required. Where absolute pressures need to be converted to gauge pressures using atmospheric pressure measurements, the original data series need to be archived as well. This allows any potential errors in the conversion process to be identified and corrected, if needed.

Currently, it appears that few studies report on the accuracy and precision of the measured hydraulic head values. This suggests that it is generally assumed that the errors associated with the measurements are so small that they do not significantly alter the outcomes of a study. This non-scientific approach is unworthy of a physical science like hydrogeology. Instead, at its onset, each study should define data quality objectives (DQOs), which are qualitative and quantitative statements that specify the quality of the data required to support conclusions or decisions (Schalla et al. 1992). Based on these, appropriate measurement methods should be chosen, and the measurement uncertainty should be quantified as well as possible. When the uncertainty is quantified, the effect of the measurement error on derived quantities, like hydraulic properties based on the head response in an aquifer test, or flow velocity based on head gradients, can be established. Especially in the case of small head gradients, even the smallest achievable uncertainties related to the head measurements (0.1–0.25 %) may sometimes lead to ±100 % uncertainty in the calculated flow velocity (Sweet et al. 1990). Quantitative information about the variance of water-level measurements can also be used to determine the appropriate contour interval for potentiometric maps (Gibbons 1990).

Although it is recognised that due to the unknown accumulation of errors (Sweet et al. 1990) it may be difficult to quantify the cumulative measurement error for heads, quantification of the error can be used to decide if the uncertainty of the measurements is small enough to meet the objectives of the study. If not, the measurement procedures may need to be reconsidered, and there may be a need to deploy more specialised techniques than those discussed here. For example, dedicated systems have been designed to measure (vertical) gradients over short distances such as in surface-water/groundwater investigations. These include a series of mini-screens attached to a manometer board (Acworth 2007) or a mini-piezometer with a differential pressure transducer (Fritz and Mackley 2009). Baldock et al. (2001) even deployed a specialized system to measure vertical head gradients in the swash zone that could resolve head gradients within the upper 35 mm of the beach surface. In another example, in confining units such as clay layers where the response times of standpipe piezometers are long, special piezometer designs (Wolff and Olsen 1968), and direct-push methods instead of drilling should be considered.

These examples show that advanced technology is available to determine heads, and the literature that describes how to obtain reliable measurements, despite being scattered across various sources, exists. Nevertheless, it seems that this knowledge has been slow to permeate hydrogeology curricula and textbooks. It is hoped that the overview of measurement techniques and associated errors presented here promotes the awareness and careful consideration of all the aspects related to the quantification of hydraulic heads.

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