
Measurement of vertical environmental-head profiles in unconfined sand aquifers using a multi-channel manometer board

R. I. Acworth

Abstract The vertical hydraulic gradient in an unconfined sand aquifer frequently exceeds the horizontal gradient when measured close to a surface discharge boundary, around an abstraction bore or close to a saline interface. The vertical gradient can be efficiently investigated using a multi-channel manometer board connected to a bundled piezometer installed using hollow-stem-auger-drilling techniques. The design and construction of a manometer board is described. Manometer board data from a site in a 30-m-deep fresh-water aquifer adjacent to a pumping bore are described. The bore is screened in the lower part of the aquifer and the impacts of partial penetration are evident on the manometer board results. Data are then described from the centre of a coastal sand spit where fresh water overlies saline water. Fluid electrical conductivity measurements from the individual tubes of the bundled piezometer are used to derive fluid density at each of the bundled piezometer ports. The average fluid density of water above the mini-piezometer port at each depth is then calculated using Gaussian quadrature. The environmental-water head profiles are compared to point-water and fresh-water head profiles and the implications of the incorrect use of point-water or fresh-water head vertical profiles are clearly demonstrated.

Résumé Dans un aquifère sableux libre, le gradient hydraulique vertical est fréquemment supérieur au gradient horizontal à proximité d'un exutoire, autour d'un forage d'exploitation ou à proximité d'une interface avec de l'eau salée. Le gradient vertical peut être étudié de manière efficace en utilisant un panneau manométrique

multi-canal connecté à un piézomètre multitube foré à la tarière creuse. La conception et la construction d'un panneau manométrique est décrite. Le présent article décrit les données d'un panneau manométrique situé dans un aquifère d'eau douce profond de 30m, à proximité d'un forage d'exploitation. Le forage est crépiné sur la partie inférieure de l'aquifère, et les impacts de la pénétration partielle paraissent évidents sur les résultats du panneau manométrique. Les données sont ensuite décrites depuis le centre d'une flèche littorale sableuse où l'eau douce se superpose à l'eau salée. Les mesures des conductivités électriques des fluides dans chacun des tubes du piézomètre multitube sont utilisées pour évaluer leur densité à chacun des ports du piézomètre. La densité moyenne de l'eau au-dessus du mini-piezomètre, à chaque profondeur, est ensuite calculée en utilisant une quadrature gaussienne. Les profils de charge hydraulique prenant en considération l'environnement sont comparés aux profils ponctuels ou aux profils d'eau douce; les conséquences de l'utilisation erronée de ces deux derniers est clairement démontrée.

Resumen Cuando se mide cerca de un límite superficial de descarga se encuentra que el gradiente hidráulico vertical, en un acuífero arenoso no confinado, frecuentemente excede el gradiente horizontal alrededor de una perforación de abstracción o cerca de una interfase salina. El gradiente vertical puede investigarse eficientemente usando un tablero de manómetro multi-canal conectado a un piezómetro atado, instalado usando técnicas de perforación tipo auger de contención en vacío. Se narra el diseño y construcción de un tablero de manómetro. Se describen los datos del manómetro en un sitio a una profundidad de 30m en el acuífero de agua fresca adyacente a un pozo de bombeo. El pozo tiene malla en la parte inferior del acuífero y los impactos de penetración parcial son evidentes en los resultados del manómetro. Los datos se describen a partir del centro de un banco costero de arena donde al agua fresca sobreyace al agua salada. Se utilizan las mediciones de conductividad eléctrica de los fluidos en los tubos individuales del piezómetro para derivar la densidad del fluido en cada uno de los puertos del piezómetro. Se calcula entonces la densidad promedio fluida del agua por encima del puerto del mini-piezómetro en cada profundidad usando la cuadratura Gaussiana. Se comparan los perfiles ambien-

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tales de presión hídrica con perfiles puntuales hídricos y de presión hídrica fresca y las implicaciones que tiene el uso incorrecto de los perfiles verticales de presión hídrica fresca o puntual hídrica son claramente demostradas.

Keywords Equipment/field techniques · Unconsolidated sediments · Coastal aquifers

Introduction

Much improved conceptual models of groundwater movement close to lakes or the ocean would be possible if the vertical variation in hydraulic head at these boundaries could be simply measured. This would be possible if a sufficient number of piezometers were installed at different depths close to the boundary; however, this is seldom carried out due to the high cost involved. The installation of a bundled piezometer offers an alternative approach. Bundled piezometers are frequently installed in sand aquifers to determine chemical variability with depth. The bundles typically comprise flexible tubes of 5 mm internal diameter strapped to the outside of a 25-mm-plastic-pipe stem. A peristaltic pump is used to extract water from the individual piezometer tubes during chemical sampling.

In this paper, the use of a multi-channel manometer board connected to the individual tubes of a bundled piezometer is described. Suction is applied to draw the water inside the tubes above ground level so that the levels can be separately observed. This method will work well for water depths within 8 m of the surface. At depths greater than 1 atmosphere equivalent (10.2 m), cavitation will occur and it will not be possible to bring the water levels above ground surface. However, many situations of interest occur where the water depths are less than this limiting value.

Data from a site adjacent to an abstraction bore in the Botany Sands Aquifer close to Astrolabe Park in Sydney are described (Acworth and Jorstad 2006). At this site, the water density is constant with depth and measurements from the manometer board can be used directly to determine the vertical hydraulic gradients associated with flow to a partially penetrating abstraction borehole.

Data from a second site in a coastal sand aquifer at Hat Head in northern New South Wales (Soriano 2003; Acworth and Dasey 2003) are also presented. At this site, there is a considerable variation in density with a saline interface at 12 m depth separating overlying low salinity water from increasing salinity water with depth. Hydraulic head calculations in variable fluid density environments are complicated by the use of different terminology. In this paper, the definitions of point-water head, fresh-water head and environmental-water heads are reviewed and the importance of only using environmental-water head to calculate the vertical hydraulic gradient in variable fluid density environments is demonstrated.

Method

Field equipment

Bundled or multi-level piezometers (Aller et al. 1989) are frequently installed to investigate water-quality variation in a sand aquifer (Lavitt et al. 1997; Acworth et al. 2000; Acworth and Dasey 2003). Several designs are possible; however, bundles consisting of a number of flexible plastic tubes—8 mm outer diameter (OD), 5 mm inner diameter (ID)—attached to the outside of a stem made from 25-mm-plastic pipe (electrical conduit) have been successfully used for many years and were employed in this study.

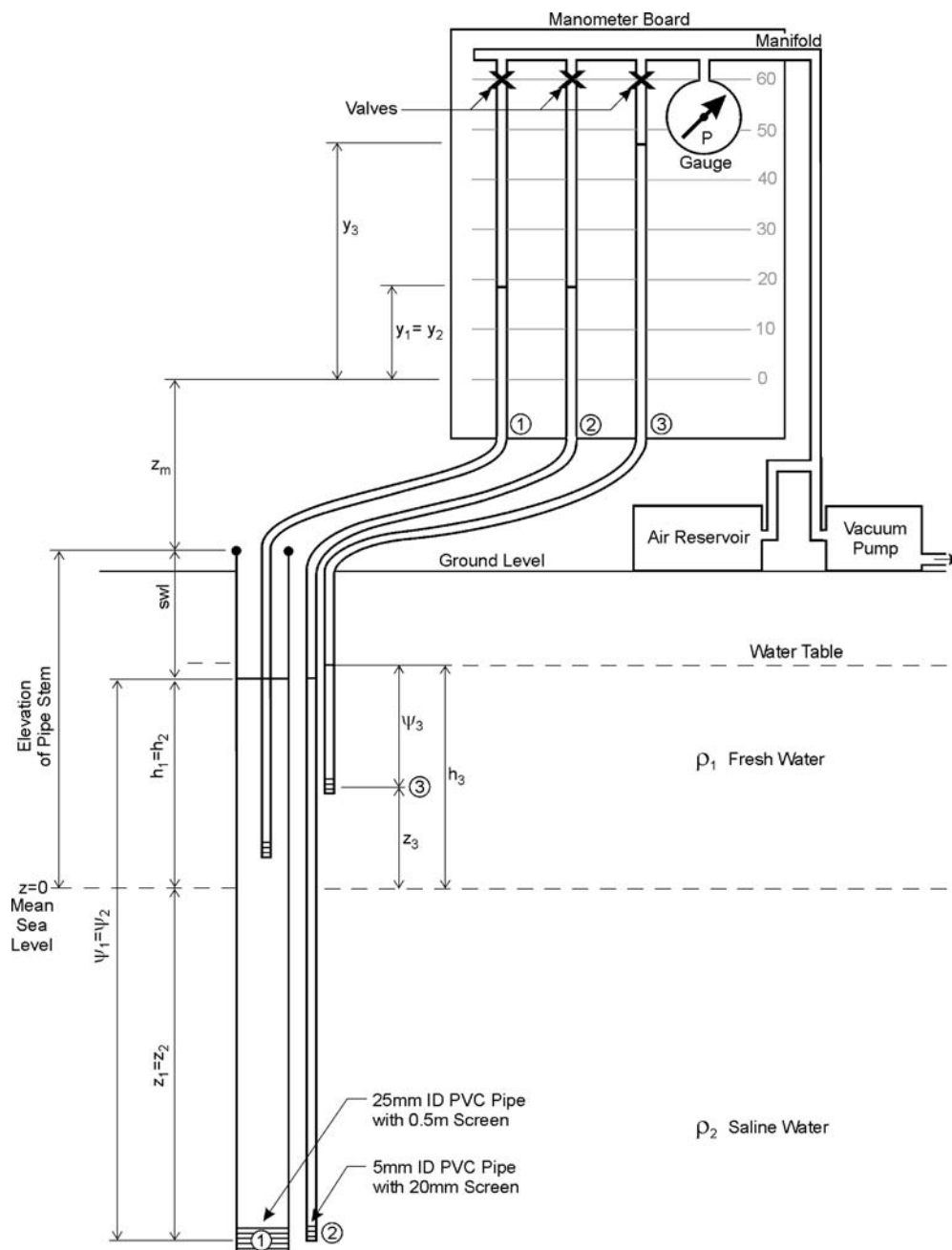
A 0.5-m section at the base of the 25-mm-ID stem was perforated and covered with geotextile to form a piezometer. Separate 5-mm-ID tubes were then fixed to the outside of this plastic pipe. Each of these mini-piezometer tubes had a 20-mm section at the end that was perforated and wrapped with a mini-sock made from geotextile fabric. The tubes were then arranged to terminate at different depths and fixed to the outside of the stem using nylon ties or plastic tape. The lowest tube (2 in Fig. 1) was fixed to terminate at the top of the screen on the 25-mm-ID-plastic pipe, as shown in Fig. 1.

The completed bundle of mini-piezometers wrapped around the 25-mm-ID stem was then installed inside hollow-stem augers that had been previously drilled to the required depth. No attempt was made to provide a seal between the mini-piezometers in the bundle and the formation was allowed to collapse back against the bundle. The tops of the mini-piezometers were clearly labelled and the elevation of the stem top determined by standard survey techniques. Each mini-piezometer was then attached to a multi-channel manometer. A generalised schematic of the equipment is shown in Fig. 1. Typically, 18 mini-piezometer tubes can be attached to the outside of the 25-mm-PVC tube to form a bundle. If greater data density is required, then a second bundle can be installed close to the first and the tubes from that also connected to the manometer board.

The manometer board can be readily fabricated from commonly available materials. Copper pipe can be used to form the air-tight manifold that the piezometers are connected to. Valves are welded into the side of the pipe with typically 15 valves per 1.2 m of pipe. Two parallel lengths of pipe are used to allow an alternate arrangement of the valves and to allow sufficient space to construct the airtight welds between the valves and the pipe. One end of each pipe is linked by a loop of high-pressure flexible hose and secured by screw clamps. A vacuum gauge can be installed on this line for an absolute pressure measurement. The remaining end has a length of flexible hose attached that can be connected through a valve to a battery-operated vacuum pump.

The pipe work can best be organised by attaching it to a backboard that can be installed above the bundled piezometer. Separate clear and rigid PVC pipes (4 mm ID and 6 mm OD) are attached to the individual valves and held in place on the backboard between strips of wood.

Fig. 1 Schematic showing the main elements of a bundled piezometer connected to a multi-channel manometer board. The head variables are as defined by Eq. (2) with the location of the reference for each of the three piezometers shown by the circled numeral indicating the channel on the board



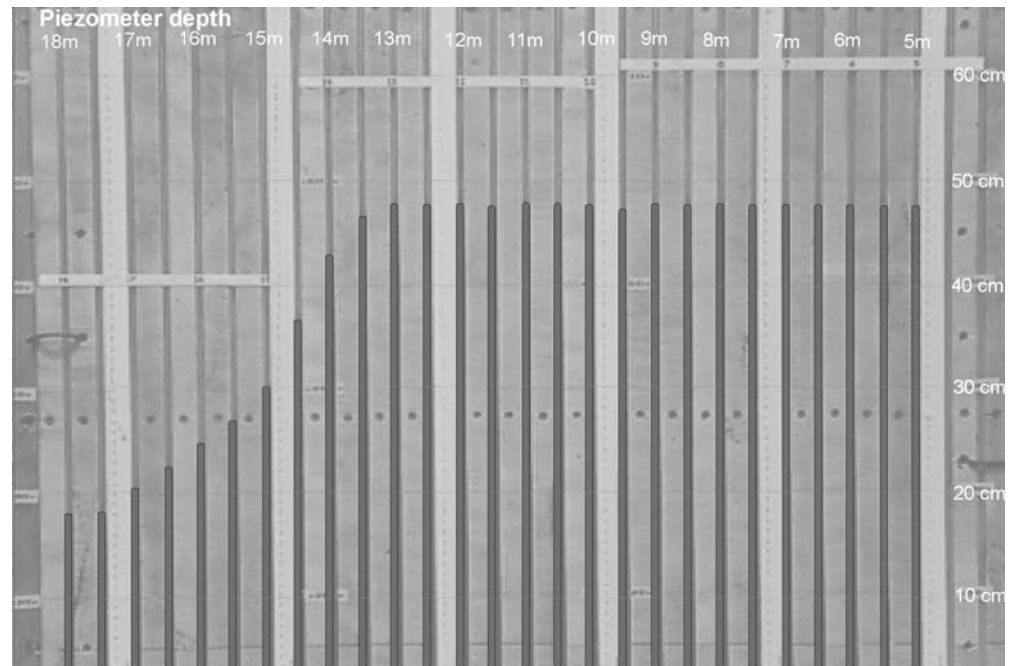
Measuring tapes are fixed to the backboard to allow accurate readings to be made (Fig. 2). The backboard is held against stakes hammered into the ground and then adjusted so that it is horizontal. The vertical distance between the zero line on the manometer board and the top of the 25 mm ID pipe (z_m in Fig. 1) is determined by survey.

The individual piezometers from the bundle are connected to the base of the tubes on the manometer board. Each valve is first closed at the manifold and then the water level in the piezometer is brought close to the surface using a peristaltic pump. If varying salinity is suspected, the fluid electrical conductivity and temperature of the water are measured. A few drops of food dye, added to the tube

before connection to the manometer board, facilitates the later observation of the water level against the measuring tapes on the board. Another useful method is to mark the back of the manometer board tube with a black line. When this is viewed through the tube, the presence of the meniscus inside the tube is readily observed.

One of the manometer board channels is connected to a tube lowered inside the central stem to the piezometer bundle and continued so that it extends below the water level (tube 1 in Fig. 1). Another tube is connected to an air reservoir provided by a 1.5 m length of 150 mm diameter thick-walled PVC pipe. When all the individual mini-piezometers have been connected to the manifold, any

Fig. 2 Example of manometer board readings from the Hat Head mid-dune site showing decreasing heads at depth. The manometer tubes connected to the deepest piezometer in the bundle at the *left* and decreasing in depth towards the *right*. Readings from this photograph provide the basis for data in Table 2



remaining valves are closed and the pump is used to develop a vacuum in the system. The water level in each of the mini-piezometers rises so that it can be observed against the measuring tapes fixed to the backboard. It is often necessary to make sure that bubbles of air that form inside the tubes by degassing are allowed to vent to the surface of the water column inside the tube.

The elevation of the meniscus in each tube (y_i in Fig. 1) is recorded against the measuring tape on the manometer board (Fig. 2). At the same time, a dip meter (water-level meter) is used to establish the depth to water—standing water level (SWL) in Fig. 1—in the 25-mm-ID stem of the bundle. A reading of the suction pressure in the manifold can be made at the same time if a pressure gauge is attached. This provides a useful check to the survey data used to determine z_m .

Data corrections for the suction pressure

The point-water head in tube 1 (25-mm-ID tube in Fig. 1) is established by subtracting the SWL from the elevation of the tube top above the datum (mean sea level in Fig. 1). This gives h_1 in Fig. 1. The levels in tubes 1 and 2 (Fig. 1) should be the same ($h_1 = h_2$) as tube 2 terminates at the top of the screen on the piezometer. Tube 2 is installed as a check on the operation of the bundled piezometer.

When a suction is applied, the levels in all tubes will rise up. Tube 1 will respond rapidly as there is almost no resistance at the base of the immersed 5-mm-ID tube inside the 25-mm-ID piezometer. In fact, care is required to control the rate of rise in tube 1 so that the water does not flood into the manifold. Other tubes will take several minutes to respond as the resistance through the 20-mm-

mini-piezometer sock and the aquifer are considerably greater. The addition of a large air reservoir to the system (Fig. 1) means that the relative change in volume (pressure) in the manifold is small and the individual response of one piezometer does not therefore affect the response of any other. A reservoir size of approximately 500 l has been used successfully.

The rest level on the manometer board (y_1 on Fig. 1) will occur when the pressure is equalised such that:

$$p = \rho_i g (y_1 + \text{SWL} + z_m) \quad (1)$$

Where p is the gauge pressure on the manometer board; ρ_i is the density of water in tube i ; g is acceleration due to gravity; y_1 is the reading on the manometer board; z_m is the distance from the top of the piezometer to the base (zero line) of the manometer board (Fig. 1) and SWL is the standing water level in the piezometer.

Clearly, if a pressure gauge is attached then all terms in Eq. (1) are completely specified, so that pressure can either be determined by measurement or by solution of Eq. (1). Conversely, Eq. (1) can be used to estimate the density ρ_i .

As the temperature of the air in the reservoir changes during the day, the gas pressure will change and the position of all the menisci will change in response. This variability is not a problem as long as the manometer board readings are all made at the same time (usually by photograph) and calibrated against a dip measurement or a pressure measurement.

If all the water in the system is of uniform salinity (density), then the corrected hydraulic head for any other mini-piezometer monitored by the board can be established by comparing it with the deviation from the

reference level established at tube 1. For example, consider the level in mini-piezometer 3 (Fig. 1); the hydraulic head for h_3 will be $h_1 \pm (y_1 - y_3)$.

For the constant density case, it is not then necessary to determine the pressure in the system and a simple water-level measurement inside the 25-mm stem is all that is required to calibrate the manometer board. Apparent hydraulic gradients can be visually observed on the manometer board and the accurate value calculated by knowing the vertical distance between the tips of the individual piezometers. In single salinity media, this is the true vertical hydraulic gradient.

Determination of point-water heads

Luszczynski (1961) defines a point-water head in ground-water of variable density, as the water level, referred to a given datum, in a well filled with water of the type at the point (base) sufficient to balance the existing pressure at the base of the piezometer. For the sake of clarity in this paper, it is worth repeating definitions of the various head terms used (see also Fig. 1). The point-water head is then:

$$h_{p,i} = z_i + p_i / \rho_i g = z_i + \psi_i \quad (2)$$

where:

- i any point in ground water of variable density
- ρ_i density of ground water at point i
- $h_{p,i}$ point-water head at i
- p_i pressure at i
- z_i elevation of i , measured positively upward
- g gravitational acceleration
- ψ_i pressure head at point i

Bundled piezometers, therefore, measure point-water heads in mixed salinity environments as the water contained in the mini-piezometer tube has come from the immediate area of the inlet (base) of the piezometer. The zone of influence and volume of water drawn into the mini-piezometer can be readily calculated. For a tube length of 18 m of 5-mm-ID tubing, the volume of water filling the tube is $3.53 \times 10^{-4} \text{ m}^3$ (353 ml). If an effective porosity of 0.15 is assumed for the sand, then the radius of the spherical volume of aquifer that contributes to this is approximately 100 mm. Porosity is typically closer to 0.3 and it can, therefore, be safely assumed that the density of the water filling the mini-piezometer tube is representative of a small volume around the piezometer intake and that the level inside the piezometer is a point-water head.

The observed heads on the manometer board are elevated above the point-water head as a result of the applied suction in the manometer board manifold. This suction is applied equally to all tubes. For the i th tube, the elevation above the point-water head level is $(y_i + z_m + \text{SWL})$, as shown in Fig. 1. The point-water heads in each mini-piezometer can be recovered by subtracting $p/\rho_i g$ from each of the observed heads, where ρ_i is the density of fluid in the tube. This correction recovers the water levels

in the ground before the suction was applied. Clearly, the density of water in each tube must be estimated to make this correction.

Density estimates

The fluid density can be estimated from the fluid electrical conductivity (EC) obtained using a standard fluid electrical conductivity meter. A peristaltic pump is connected to the tube of the mini-piezometer and approximately 250 ml of water delivered to a beaker where the EC measurement is made. Many commonly available meters provide an automatic correction to 25°C. This is typically calculated based on the assumption that the fluid is a solution of potassium chloride with a temperature dependence on fluid EC of 2.2% per °C.

The fluid density (ρ in kg/m^3) can be estimated from the fluid EC using the relationship after Stuyzfand (1993) developed for coastal areas and sand aquifers in The Netherlands:

$$\rho = 1000 \times \left(1 + 8.05 \times 10^{-7} \times \text{RE} - 6.5 \times 10^{-6} \cdot (T - 4 + 2.2 \times 10^{-4} \times \text{RE})^2 \right) \quad (3)$$

Where T is the fluid temperature and RE is the residue on evaporation at 180°C (mg/kg). This can be approximated from the expression:

$$\text{RE} = 0.69778 \times \text{EC}_{20} \quad (4)$$

where EC is the fluid conductivity in $\mu\text{S/cm}$ at temperature 20°C. As the fluid EC is frequently standardised to a temperature of 25°C, it is necessary to account for this temperature difference using the relationship after Stuyzfand (1993):

$$\text{EC}_{20} = \text{EC}_{25} \times (1 + 0.23 \times (T_{20} - T_{25})) \quad (5)$$

For a 5° temperature change this becomes $\text{EC}_{20} = \text{EC}_{25} \times 0.85$.

The residue on evaporation (RE) can also be estimated from the chloride content if this has been measured on the samples (Stuyzfand 1993):

$$\text{RE} = 1.805 \times \text{Cl}^- + 30 \quad (6)$$

where the chloride (Cl^-) content is expressed as mg/kg (equivalent to mg/l in weak solutions). This provides a useful check on the density derived solely from fluid EC.

Calculation of fresh-water head

The fresh-water head at any point in the ground is defined (Luszczynski 1961; Holzbecher 1998) as the head that would be developed in a variable density system if the pressure at the piezometer intake was generated by an equivalent column of fresh water. For waters that have

higher salinity contents than fresh water, the head will be higher than the point-water head. The fresh-water head is then:

$$h_{f,i} = h_{p,i}\rho_i/\rho_f - z_i(\rho_i - \rho_f)/\rho_f \quad (7)$$

where ρ_f is the density of freshwater commonly taken as 998.3 kg/m³.

Calculation of environmental-water head

Luszczynski (1961) demonstrates that fresh-water heads only define the hydraulic gradient in a variable salinity medium when measured in a horizontal plane. By contrast, environmental-water heads are required to define the hydraulic gradient in the vertical plane. Luszczynski (1961) also notes that when the measurements are made with reference to mean sea level as the datum, the environmental-water head can be defined in terms of the point-water head as:

$$h_{e,i} = h_{p,i}\rho_i/\rho_f - z_i(\rho_i - \rho_a)/\rho_f \quad (8)$$

where:

- i any point in ground water of variable density,
- ρ_a average density of ground water between mean sea level and point i,
- ρ_i density of water at point i,
- ρ_f density of freshwater (998.3 kg/m³),

- $h_{p,i}$ point-water head at i,
- z_i elevation of i, measured positively upward,
- g gravitational acceleration

The difficulty of obtaining an average fluid density value between mean sea level and the reference point has meant that there has been little application of the environmental-head approach. Instead, the more easily calculated fresh-water head has been determined or, the significance of density variation has been ignored and the point-water head has been applied.

The combination of a bundled piezometer and a manometer board provides an alternative approach. The fluid density at each depth can be calculated from the relationships given above—Eqs. (3, 4, 5 and 6). The average density between mean sea level and a specific depth can be determined from Eq. (9).

$$\rho_a = \frac{1}{z_i} \int_0^{z_i} \rho dz \quad (9)$$

Gaussian quadrature, using either the mid-point approach or Simpson's rule, can be used to solve Eq. (9) at the required depths. Simpson's rule is generally considered more accurate than the mid-point theorem but both approaches gave results that were practically identical (0.0008% difference) for the total integration (between 0 and -16 m) and the more readily applied mid-point approximation has been used to calculate the average densities as shown in Table 1.

Table 1 A comparison of density and average density profiles using fluid EC and chloride content data from Hat Head in northern New South Wales, sampled in June 1999

Depth (m)	Fluid EC (μS/cm)	Fluid temperature (°C)	Chloride (mg/l)	Density ^a based upon fluid EC (kg/m ³)	Density ^b based upon chloride content (kg/m ³)	Fluid EC derived ^c ρ_a (kg/m ³)	Chloride content derived ^c ρ_a (kg/m ³)
10	395	18.4	54	998.8	998.7	998.98	998.84
10.5	473	18.5	80	998.9	998.8	998.97	998.83
11.0	588	18.3	115	998.9	998.9	998.96	998.83
11.5	744	18.4	155	999.0	998.9	998.97	998.84
12.0	765	18.1	142	999.1	989.9	998.97	998.84
12.5	722	17.7	150	999.1	999.0	998.97	998.84
13.0	1,033	17.3	260	999.3	999.2	998.99	998.86
13.5	3,580	17.0	1,055	1000.6	1000.4	999.03	998.90
14.0	11,500	17.6	3,658	1004.2	1003.9	999.16	999.02
14.5	21,200	17.5	6,915	1008.8	1008.4	999.44	999.30
15.0	29,100	18.3	9,950	1012.3	1012.3	999.85	999.70
15.5	32,400	18.9	11,105	1013.7	1013.7	1000.32	1000.18
16.0	36,000	19.1	12,600	1015.3	1015.7	1000.81	1000.68
16.5	39,200	18.6	13,520	1016.9	1017.1	1001.32	1001.20
17.0	41,300	18.3	14,446	1018.0	1018.4	1001.83	1001.73
17.5	43,500	18.3	15,166	1019.0	1019.4	1002.35	1002.27
18.0	43,200	18.1	15,108	1018.9	1019.3	1002.85	1002.78

^a Using Eq. (5) to correct field EC reported at 25°C to EC at 20°C; then Eq. (4) to calculate RE; then Eq. (3) to calculate density

^b Using Eq. (6) to calculate RE from the Chloride data and Eq. (3) to calculate density

^c Average density calculated by Gaussian quadrature using the mid-point method

Geophysical logging

Geophysical logs were run in adjacent observation bores using a gamma-ray activity sonde to detect clay bands and a bulk electrical conductivity sonde (GEONICS EM39) to detect changing fluid EC or clay content. In each case, the geophysical access bores were less than 2 m from the bundled piezometers. These logs are used to support the EC determinations in the bundled piezometer and provide independent corroboration of the results.

Results

Abstraction bore in the Botany Sands Aquifer-Sydney

A bundled piezometer was installed 12 m from an abstraction bore in the Botany Sands Aquifer in Sydney. The aquifer at this location comprises clay-free, aeolian sands to bedrock at 32 m, becoming silty in the last 4 m above sandstone bedrock. Thin zones of organically cemented sands occur in discontinuous layers in the upper part of the sequence (Webb and Watson 1979). The water quality in the aquifer is uniform with a fluid EC of $<200 \mu\text{S}/\text{cm}$ and a temperature of between 19 and 20°C .

Mini-piezometers were installed in a bundle with 20-mm-long screens set every metre from 4 m to the base of the aquifer at 32 m. The water table was approximately 6.6 m below ground level and the mini-piezometers above 10 m were not connected to the manometer board. The hydraulic head results obtained prior to pumping and while pumping at approximately 8 l/s from the abstraction bore are shown in Fig. 3.

Hat Head-sand dunes

A bundled piezometer was installed mid-way between the ocean and a tidal creek at Hat Head in northern New South Wales (Acworth and Dasey 2003). The site was approximately 160 m from the ocean and saline water was encountered at approximately 13 m depth beneath low-salinity water. Water levels in piezometers installed at 9 and 18 m adjacent to the bundled piezometer were recorded hourly over a 3-month period. An extract from this data is presented in Fig. 4 and indicates little variation in difference between the levels. The data was recorded using pressure transducers (DRUCK PDCR830) and has not been corrected for density.

Fluid electrical conductivity profiles were collected twice during 1999. In June, the full chemistry was determined for each mini-piezometer. In December, only the fluid EC and temperature were recorded prior to setting up the manometer board. Gamma ray activity and bulk EC logs were carried out in the bore in July 1999.

The density estimates were checked using the fluid EC—Eqs. (3), (4) and (5)—and chloride content—Eqs. (3) and (6)—measured on water samples in June 1999, at the same time the geophysical logs were obtained. The results, shown in Table 1, demonstrate that there are only small variations in the density estimate using the two different methods. The profiles of average density shown in Table 1 have been calculated using the mid-point theorem for both the fluid EC and the chloride derived density data. Note also that the calculation of the average value further diminishes any inaccuracy in the individual data values.

Values of y_i for all mini-piezometers can be calculated from Fig. 2 and are shown for the lower part of the profile

Fig. 3 Hydraulic heads adjacent to a pumped bore in the Botany Sands Aquifer in Sydney. The abstraction bore screen is set at the base of the aquifer

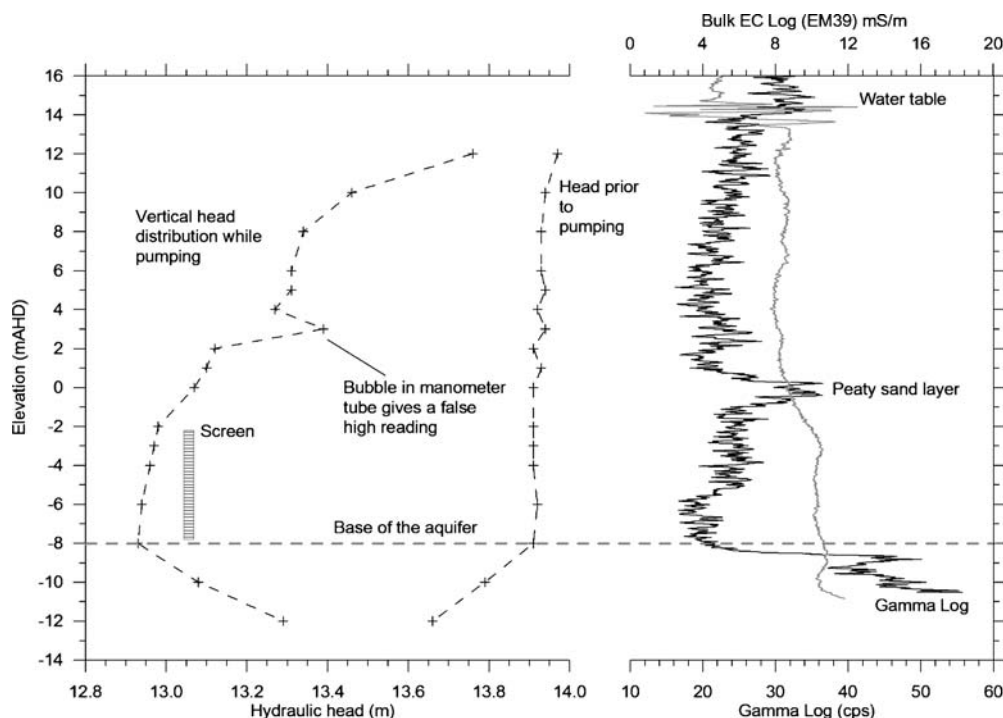
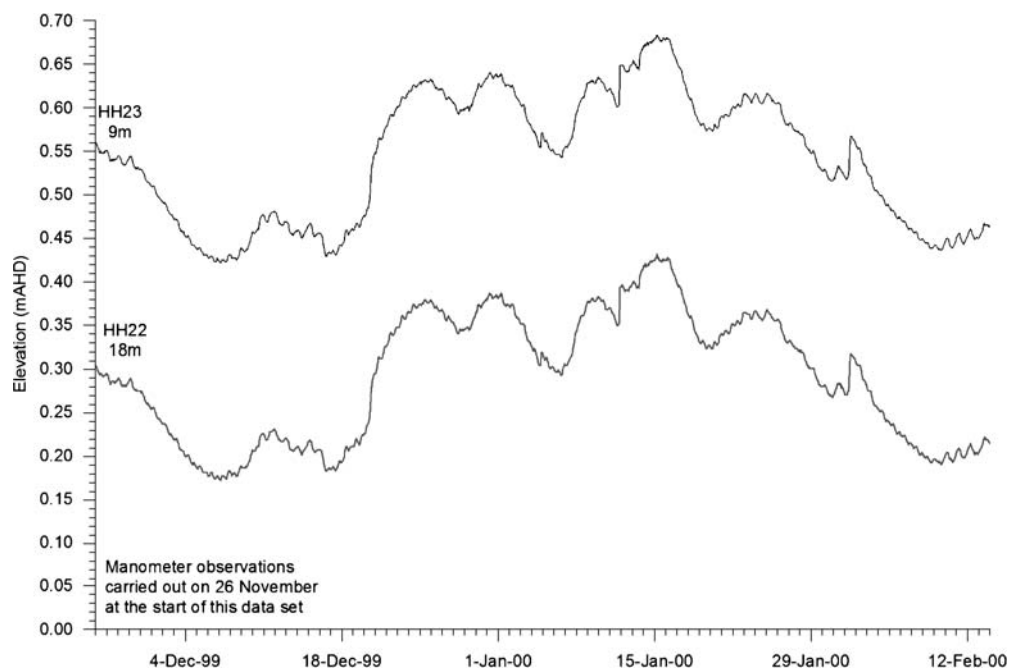


Fig. 4 Water-level elevations at 9 and 18m beneath the sands at the mid-dune site



in Table 2. The value of z_m for this set up was 0.608 m; the SWL in the shallow piezometer (HH23) was 0.905 m and the elevation of the top of the pipe was 1.455 m. The required calculations can easily be made using a spread-

sheet and the equations presented above. The point water, fresh water and environmental-water heads produced by these analyses are shown in Table 2 and Fig. 5.

Table 2 Manometer board data for the sand dunes site at Hat Head, New South Wales

Z^a (m)	Fluid EC ^b ($\mu\text{S}/\text{cm}$)	Density at port ^c ρ_i (kg/m^3)	Average density ^d ρ_a (kg/m^3)	Height on board ^e (cms)	Total head on manometer board ^f (m)	Point-water head ^g $h_{p,i}$ (m)	Fresh-water head ^h $h_{f,i}$ (m)	Environ.-water head ⁱ $h_{e,i}$ (m)
-8.54	305.3	998.4	998.5	47.9	2.542	0.552	0.553	0.551
-9.04	374.4	998.5	998.5	48.1	2.544	0.554	0.556	0.554
-9.54	473.5	998.5	998.5	48.0	2.543	0.553	0.555	0.553
-10.04	583.2	998.6	998.5	47.8	2.541	0.552	0.554	0.552
-10.54	621.3	998.6	998.5	47.9	2.542	0.552	0.556	0.553
-11.04	559.3	998.5	998.5	48.1	2.544	0.554	0.557	0.555
-11.54	812.4	998.7	998.5	48.0	2.543	0.554	0.558	0.555
-12.04	2,619.6	999.5	998.6	46.9	2.532	0.544	0.559	0.556
-12.54	9,097.8	1,003.1	998.7	43.1	2.494	0.513	0.575	0.571
-13.04	17,098	1,007.3	998.9	36.6	2.429	0.456	0.578	0.570
-13.54	25,134	1,011.5	999.3	30.2	2.365	0.369	0.584	0.571
-14.04	28,497	1,013.2	999.8	26.7	2.330	0.350	0.584	0.563
-14.54	31,240	1,014.6	1,000.2	24.5	2.308	0.329	0.594	0.565
-15.04	33,541	1,015.8	1,000.7	22.2	2.285	0.314	0.599	0.562
-15.54	36,196	1,017.2	1,001.3	20.4	2.267	0.288	0.614	0.568
-16.04	38,320	1,018.3	1,001.8	17.6	2.239	0.286	0.615	0.559
-16.54	38,940	1,018.6	1,002.3	17.4	2.237	0.294	0.628	0.562

^a z is elevation below datum of the mini-piezometer port

^b Fluid EC has been corrected for temperature using Eq. (5)

^c Density calculated using Eq. (3)

^d Average density between port i and datum—calculated using Eq. (9). Gaussian quadrature achieved using the mid-point method

^e Heights of water in the manometer board tubes as shown in Fig. 2

^f Total head above datum of water in the manometer board tubes is the sum of: the height on the board (y); the height of the board zero above the top of the pipe (z_m); the depth from the top of the pipe to the water level (SWL); and the elevation of the water in the pipe above datum

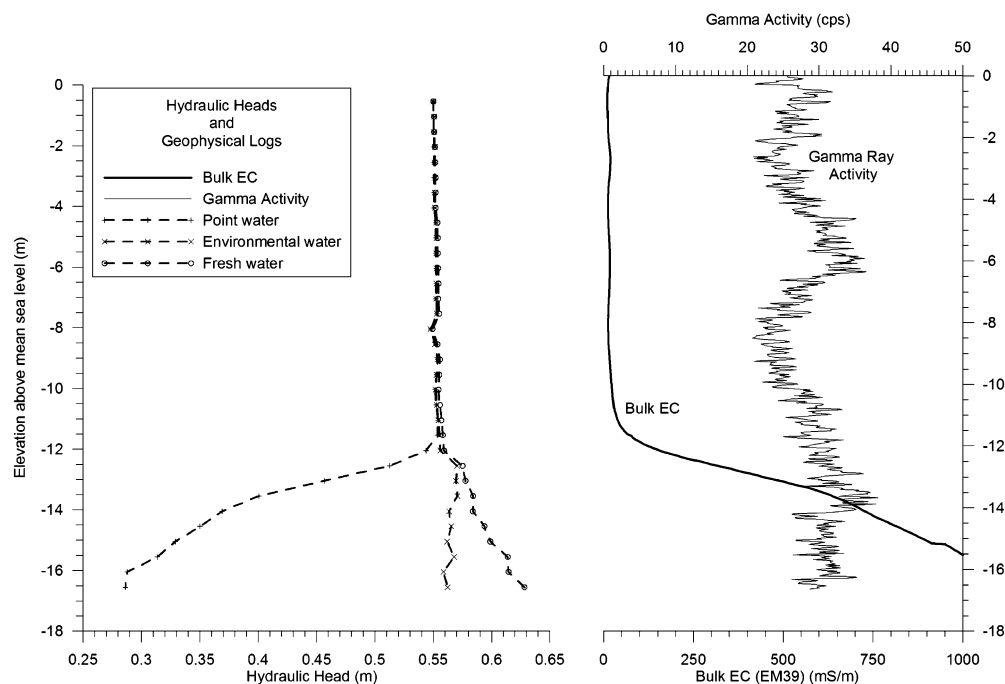
^g Point-water head calculated from total head using Eq. (2). The pressure was calculated to be 19.49 kPa—derived from the pressure head

^h Fresh-water head calculated using Eq. (7)

ⁱ Environmental-water head calculated from Eq. (8)

Table shows data for the lower part of the profile only. The board suction was recorded on a gauge as 19.52 kPa

Fig. 5 Environmental, point and fresh-water heads for the central part of the sand aquifer at Hat Head where fresh water overlies saline water. Gamma and bulk electrical conductivity logs shown confirm location of base of fresh water and the clay free nature of the sands



Discussion

Abstraction bore in the Botany Sands Aquifer-Sydney

The geophysical logs of the bore (Fig. 3) confirm that the lithology is dominantly sand (low gamma-ray activity) and is saturated with low salinity groundwater (low Bulk EC). Therefore, the water in this bore will have a constant density and corrections are not required for variation in groundwater density. The hydraulic gradient is then accurately shown from the point-water head data.

The hydraulic head distribution before pumping commenced shows a very low uniform vertical hydraulic gradient extending throughout the aquifer to the top of the silty sands at -8 m AHD (Australian Height Datum; Fig. 3). The gradient is slightly negative (-0.004), indicating a small component of downward flow in the sands. A more significant (-0.063) vertical gradient exists between -8 and -12 m at the base of the aquifer, indicating a downward flux from the sands into the underlying sandstone with head loss occurring in the silty sands indicated on the gamma log. Repeated results 12 months later (not shown) show a vertical gradient of -0.117 . This is considerably greater than the horizontal gradient across the site which is at least two orders of magnitude smaller. These observations are of interest as the boundary has been assumed to be impermeable (no flow) in groundwater models of the Botany Sands Aquifer (Merrick 1998). More recently, a further piezometer has been completed in the top of the underlying sandstone. The elevation of the piezometric surface in the sandstone confirms a negative gradient from the sands to the sandstone at this site.

The vertical hydraulic head distribution while pumping shows approximately 1.03 m drawdown adjacent to the screen. This is confirmed by observations in other piezometers (not shown). Below the screen, the hydraulic gradient (0.225) has been reversed with water moving upward (positive gradient) from the silty sand to the main aquifer. In the zone above the screen to the top of the aquifer, a more pronounced negative gradient (-0.075) develops as water drains through the aquifer towards the screened section of the aquifer. The lack of a constant hydraulic head adjacent to the 6 m of screen suggests that either the aquifer hydraulic conductivity is not as uniform as expected, or possibly that the gravel pack in the abstraction bore is not uniformly placed.

A study of the delayed drainage from a long duration aquifer test is planned and repeated monitoring using a manometer board will provide useful information on the expected development of iron fouling in the abstraction bore. This bore has recently been replaced due to extensive corrosion in an older installation close by.

Hat Head-sand dunes

The salinity distribution (Fig. 5) at this site is typical of many sand aquifers close to the coast. The zone below the interface does not represent sea water but a mixing or diffusion zone where the salinity increases towards sea-water salt concentrations over more than 6 m. The hydraulic environment of this bundled piezometer site is such that fairly static conditions are expected with no vertical movement. The data were measured after a long period of dry weather and therefore recharge would have

been minimal. The presence of the high salinity water in the deeper part of the aquifer is shown by the bulk EC log. Drilling at this site encountered only sand (Soriano 2003).

The point-water head profile (Fig. 5) is the same shape as that shown on the manometer board (Fig. 2). The offset between the individual piezometer records from depths of 9 and 18 m (0.252 m shown in Fig. 4) at the start of the logging period is similar to the difference in point-water heads (0.258 m shown in Table 2 and Fig. 5) calculated from the manometer board data. Note that the difference in heads measured by the manometer board (0.305 m in Fig. 2) is increased as a result of the applied suction. There is a clear negative gradient in point-water head that would indicate downward movement of groundwater if the density distribution was not considered.

Correcting the heads to represent a fresh-water head profile (Fig. 5) reverses the gradient at depth and could lead to similar erroneous conclusions regarding groundwater flow with the suggestion of upward movement of water. The point-water and fresh-water heads diverge with increasing depth.

The profile of environmental-water heads is also shown on Fig. 5. There is no significant vertical gradient between 0 and 12.5 m and again between 14 m and the base of the bore. There is a small (20 mm) step change between 13 and 13.5 m. This step change appears real and, if true, would indicate that the environmental-water head is not completely in hydrostatic equilibrium. To establish the veracity of the step change, a number of further checks were carried out. Clearly, the fluid EC used to establish

density may be in error. The range of fluid EC at this location covers a scale change on the meter (at 2,000 $\mu\text{S}/\text{cm}$). To check if an error in the linearity of the meter could explain the step, values greater than 1,000 were adjusted by small (1%) increments; however, a hydrostatic profile was not achieved by this process. To check the linearity of the meter, fluid EC was plotted against TDS (total dissolved solids) measured in the June 1999 sampling data (Fig. 6). This plot confirms that the fluid EC is linearly related to the TDS ($\text{TDS} = 0.716 \times \text{EC}$; $r^2 = 0.964$) and that a scale error on the meter is unlikely to be the cause of the small step change in environmental head. The small increment of head at the top of the saline zone appears to be real and requires a hydraulic explanation that is not immediately apparent. It is important to note that the environmental-water head profile remains a significant improvement on either the point-water or freshwater-head profiles.

Conclusion

A multi-channel manometer board connected to a bundled piezometer can be used in sand aquifers saturated with either constant salinity or variable salinity water to enable data on the vertical distribution of hydraulic head to be gathered. The equipment is not difficult to construct or use in the field. It clearly requires more field time to acquire the data than a single bore measurement; however, the additional data allows the correct hydraulic gradients to be established from which a much-improved conceptual model for the system can be developed. In uniform temperature and density (salinity) water, the hydraulic gradients can be determined directly from the head readings on the manometer board. This provides a rapid means of evaluating possible flow directions and can significantly add to the value of field investigations and to the interpretation of pumping tests. The profile of point-water heads (h_p) in what was previously expected to be low salinity water can also indicate higher densities associated with a contamination plume. For this reason, the technique has a general applicability.

In groundwater of variable salinity, Luszczynski (1961) and De Wiest (1969) have demonstrated that it is necessary to calculate the environmental-water heads before an accurate vertical hydraulic gradient can be determined. The average density of water between the reference point and the datum is required for this calculation. The construction of a multi-channel manometer board and connection to a bundled piezometer with mini-piezometers every 500 mm allows a density profile to be established which is sufficiently accurate for many coastal studies. The density can be estimated with sufficient accuracy from the fluid EC of water in the bundled piezometer tubes. Accurate measurements of water depth in the 25 mm bundled piezometer stem and elevation survey data are all that are required to calculate the environmental-water head profile.

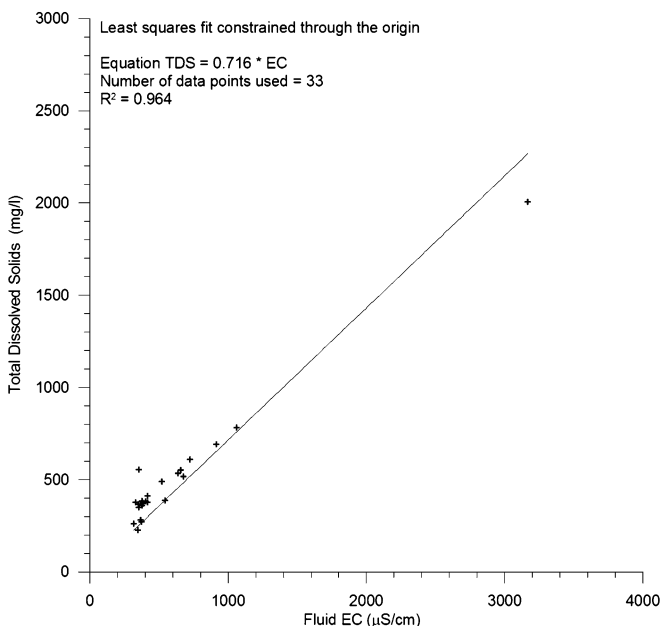


Fig. 6 Plot showing a linear relationship between fluid EC and total dissolved solids calculated from the chemical analysis of water samples taken during the June 1999 sampling event

The use of fresh-water or point-water heads is shown to produce implausible hydraulic gradients at a field site underlain by variable density water. At the base (−16 m below sea level) of the measured profile, the point-water head underestimates the environmental-water head by 268 mm while the fresh-water head overestimates by 66 mm. The underestimate leads to a false indication of upward flow while the overestimate leads to a false indication of downward flow. With the exception of a 20 mm step at the interface between fresh water and the top of the saline plume, the environmental-water head shows almost no vertical gradient and confirms only lateral flow at this location in agreement with the overall conceptual model of the site (Acworth and Dasey 2003). This analysis provides a practical proof to Lusczynski's (1961) theoretical analysis and highlights the danger of using either point-water head or fresh-water heads in the analysis of vertical hydraulic head variation in a sand aquifer saturated with variable salinity water.

The manometer board can be used to derive vertical profiles of environmental-water head in sands saturated with variable salinity water. This will allow collection of important additional data to help develop conceptual models in locations such as the coastal zone where hydraulic head variation and chemical mixing occur (Acworth and Andersen 2004). Interpretation of hydrochemical processes in the coastal zone in response to major tidal variations, salt water overtopping during spring high tides, or the mixing between regional groundwater discharge and sea water will be greatly facilitated by the availability of accurate vertical hydraulic head data.

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