Vertical groundwater storage properties and changes in confinement determined using hydraulic head response to atmospheric tides

Citation:

DOI: http://www.dx.doi.org/10.1002/2016WR020311

© 2017, American Geophysical Union
Reproduced with permission.

Downloaded from DRO:
http://hdl.handle.net/10536/DRO/DU:30115014
Vertical groundwater storage properties and changes in confinement determined using hydraulic head response to atmospheric tides

R. Ian Acworth¹,², Gabriel C. Rau¹,², Landon J. S. Halloran¹,², and Wendy A. Timms¹,³

Abstract Accurate determination of groundwater state of confinement and compressible storage properties at vertical resolution over depth is notoriously difficult. We use the hydraulic head response to atmospheric tides at 2 cpd frequency as a tracer to quantify barometric efficiency (BE) and specific storage (Ss) over depth. Records of synthesized Earth tides, atmospheric pressure, and hydraulic heads measured in nine piezometers completed at depths between 5 and 55 m into unconsolidated smectitic clay and silt, sand and gravel were examined in the frequency domain. The barometric efficiency increased over depth from ~0.05 in silty clay to ~0.15 in sands and gravels. BE for silty clay was confirmed by calculating the loading efficiency as 0.95 using rainfall at the surface. Specific storage was calculated using effective rather than total moisture. The differences in phase between atmospheric pressure and hydraulic heads at 2 cpd were ~180° below 10 m indicating confined conditions despite the low BE. Heads in the sediment above a fine sand and silt layer at 12 m exhibited a time variable phase difference between 0° and 180° indicating varying confinement. Our results illustrate that the atmospheric tide at 2 cpd is a powerful natural tracer for quantifying groundwater state of confinement and compressible storage properties in layered formations from hydraulic heads and atmospheric pressure records without the need for externally induced hydraulic stress. This approach could significantly improve the development of conceptual hydrogeological model used for groundwater resource development and management.

1. Introduction

In groundwater resources, the term “semiconfined” is widely used but not clearly defined. Semiconfinement must represent a spatial zone in which there is a transition between an unconfined aquifer containing a water table and a confined aquifer where the hydraulic (piezometric) head is encountered above the top of the confining layer [Domenico and Schwartz, 1998]. While upward leakage from the confined aquifer through the semiconfined aquifier is clearly possible, downward leakage can only occur if the hydraulic head in the confined system is lowered below that of the head in the semiconfined system. Downward leakage is therefore not a natural occurrence and can only be generated by groundwater abstraction from the underlying aquifer. Consequently, there is no natural precedent to help predict the impacts of groundwater abstraction in the semiconfined zone.

The concepts of aquifer storage in both unconfined and confined systems are well defined [e.g., Freeze and Cherry, 1979]. For example, the unconfined storage may be as high as 0.3 (300 L/m³) in a well-sorted sand aquifer where specific yield describes the relationship between the volumetric water content and the water level [Domenico and Schwartz, 1998]. However, the specific storage (confined aquifer storage term which relates the water released from compressible storage to the corresponding change in hydraulic head) is a function of both the compressibility of water and the compressibility and porosity of the formation. This concept is complicated by the appreciation that the aquifer may deform when the water pressure is reduced and the use of a material coordinate system is required [Domenico and Schwartz, 1998]. However, the volume of water produced by a unit reduction in hydraulic head in a confined aquifer is very much less than the specific yield, typically between 10⁻⁷ and 10⁻⁵ m³ (0.1–10 mL). Consequently, the simple
identification of an aquifer as being either confined or unconfined has significant implications for ground-
water resource development and management.

Quantifying aquifer hydraulic properties or inferring groundwater confinement generally requires intrusive
methods such as drilling, coring, or observing the hydraulic head response to hydraulic stresses (e.g., pump-
ing). Pumping tests in particular require significant effort especially when aquifer properties are required at
high spatial resolution or when lower permeability units (i.e., aquitards) are to be characterized hydraulically.
Analyzing pumping test results in order to map the spatial distribution of hydraulic properties requires
information about lithology and confinement in order to develop the correct conceptual model tied to the
subsequent inversion of the head response. Inverted aquifer properties are potentially nonunique, the accu-
racy depends on the number of points in space at which the system is stressed and at which observations
are made.

Groundwater hydraulic heads are affected by natural stresses. For example, daily head oscillations have
been identified as caused by evapotranspiration from vegetation under unconfined conditions [e.g., Gri-
obovszki et al., 2010; Acworth et al., 2015b]. Hydraulic head oscillations caused by small changes in gravity
over time (Earth tides) or tide-induced atmospheric pressure changes (atmospheric tides) are a common
occurrence. Under confined conditions, this is driven by both Earth and atmospheric tides [Merritt, 2004].
Earth tide oscillations have been used to calculate formation permeability and compressible groundwater
storage properties in deep and fractured aquifers [Hsieh et al., 1987; Burbey et al., 2012; Allègre et al., 2016].
In particular, Cutillo and Bredehoeft [2011] illustrate how aquifer specific storage can be calculated from
Earth tide strains, which would lead to porosity estimates given barometric efficiency. However, these works
are based on confined conditions.

Acworth et al. [2016a] developed a relatively simple method that exploits hydraulic head variations induced
by atmospheric tides at 2 cpd as a tracer to accurately calculate barometric efficiency (BE) and confined
groundwater storage properties. They calculated results for three different locations spanning across the BE
range (0 ≤ BE ≤ 1). Further, they hinted that confined conditions show as a 180° phase difference between
atmospheric pressure and hydraulic heads. To the best of our knowledge, this method has not been applied
to calculate storage properties across a vertical sediment sequence, verified against other methods and
investigated in regards to its capability to determine state of confinement.

In this paper, we illustrate that the groundwater response to barometric tides at 2 cpd can be used to accu-
rately quantify BE and infer storage properties over depth in a sediment sequence consisting of low perme-
ability clays. We illustrate this using head data from a site with piezometers screened at discrete depths and
verify the results using independent loading efficiency calculations derived from the hydraulic head
response to rainfall events [Timms and Acworth, 2005; Rasmussen and Mote, 2007]. Further, we pursue the
hint by Acworth et al. [2016b] about the determination of confinement and demonstrate that the phase dif-
fERENCE between hydraulic head and atmospheric pressure at 2 cpd frequency can be used to identify the
transition zone between unconfined and confined, and that this transition zone can undergo temporal
changes related to rainfall at the surface. Our results illustrate that atmospheric tides can be used to quanti-
fy confined storage properties in situ over depth, to investigate the spatiotemporal behavior of the semi-
confined zone and to develop improved conceptual groundwater models.

2. Methodology

2.1. Field Site Description and Previous Work
Piezometers at 8 m horizontal and 5 m vertical intervals have been established within separate boreholes at
a site on the Liverpool Plains of northern New South Wales, Australia (Figure 1). The eight piezometers,
between 5 and 40 m depth (CL-5 to CL-40) complement an existing borehole into sand and gravels at 55 m
(GW30061, see Figure 1a). The screened sections on the piezometers are 1 m long, whereas the screened
section on the borehole is 6 m. The sequence of nine different discrete depths allows a detailed vertical
characterization of the groundwater hydraulic response to stresses.

A sediment core to 31.5 m depth was also taken and the material thoroughly characterized by Acworth
et al. [2015a]. The alluvial deposits at this site have accumulated from intermittent weathering of the sur-
rounding Triassic sandstone hills during pluvial periods and the slow accumulation of smectite clay-
Figure 1. Map showing the location of the field site in (inset a) Australia, (b) Cattle Lane on the Liverpool Plains and the boreholes as well as climate station used in this investigation (Figure 1a).
dominated soils during drier periods. The clay is derived from the weathering of Miocene alkali basalts on the Liverpool Ranges approximately 25 km to the south (Figure 1b). Optically stimulated luminescence and radio-carbon data from shells demonstrate that the profile to 31 m depth has accumulated during the past 120 ka [Acworth et al., 2015a].

Electromagnetic induction logs (Geonics EM53) for all piezometers demonstrate the lateral extent and continuity of the deposits at this site. In Figure 2, the geophysical logs are shown with the particle size distribution data (PSD) taken from the base of each of the 21 cores. The sediment is dominated by smectite clay with interspersed lens of silt, sand, and gravel. The layer sandy silt 12–14 m (Figure 2) required casing during construction as it continued to move into the drill hole.

*Figure 2.* Bulk electrical conductivity logs for all piezometers at Cattle Lane, together with sediment particle size distribution data, are plotted against depth. The Geonics EM53 induction sonde was used in each of the piezometers and the profiles plotted on the same depth axis. The particle size data come from samples taken from the core nose of each of the 21 cores taken [Acworth et al., 2015a].
2.2. Monitoring Hydraulic Heads, Atmospheric Pressure, and Rainfall

Vented pressure transducers (Level Troll 700H, In-Situ Inc., USA) were installed at each location with the atmospheric pressure recorded at the site using an absolute gauge transducer (Baro Troll, In-Situ Inc., USA) inside an adjacent borehole on site (GW 40822, see Figure 1a).

Hydraulic head and atmospheric pressure measurements were recorded hourly for a period of 8 months between January and August 2016. This sampling frequency is high enough to allow extraction of useful Earth and atmospheric tide components in hydraulic heads as the upper limit for frequency detection (Nyquist frequency) is 12 cpd. The bores were manually dipped at the beginning and end of the monitoring period. Surface positions were established using a differential GPS system (Trimble GNSS R10), and a laser level was used to determine accurately the relative elevations of all measuring points.

Rainfall and general climate observations were recorded using a weather station (Campbell Scientific) installed on a Triassic sandstone hilltop at Paringa, approximately 3.8 km to the southeast (Figure 1b). Rainfall data were summed to 09:00 each day. The Penman-Monteith formula [Allen et al., 1998] was used to calculate potential evapotranspiration from the climate data.

2.3. Relationships for Compressible Formation Properties Under Confined Conditions

Under undrained conditions, the subsurface barometric efficiency (BE) is defined as

\[ BE = \frac{\Delta h}{\Delta p}, \]

where \( \Delta p \) is an atmospheric pressure change and \( \Delta h \) is a corresponding change in hydraulic head. Further, \( BE \) and the loading efficiency \( \gamma \) are related by [Jacob, 1940; Van Der Kamp and Gale, 1983]

\[ BE + \gamma = 1. \]

The loading efficiency can be expressed as the ratio of terms involving aquifer compressibility

\[ \gamma = \frac{\alpha}{\beta + \alpha}, \]

where \( \alpha \) is the formation compressibility (Pa\(^{-1}\)), \( \beta \) is the fluid compressibility (Pa\(^{-1}\)) (4.59 \times 10\(^{-10}\) Pa\(^{-1}\) at 20°C), and \( \theta \) is the formation porosity. The value of specific storage (m\(^{-1}\)) for the confined formation is [Cooper, 1966]

\[ S_s = \rho g (\alpha + \theta \beta). \]

An alternative equation for specific storage can be developed by rearranging equation (3) to solve for formation compressibility \( \alpha \) and substituting into equation (4) resulting in

\[ S_s = \rho g \frac{\theta}{BE} = 4.5 \times 10^{-6} \frac{\theta}{BE}. \]

Here only the value of porosity \( \theta \) is unknown but constrained to a range between zero and a maximum porosity of \( \approx 0.5 \). The choice of an appropriate value for porosity for the above equations, for example total or effective, is discussed in section 4.1.

2.4. Barometric Efficiency Calculation in the Frequency Domain

We provide a brief summary of Acworth et al. [2016a] before applying, verifying, and expanding this methodology to more comprehensively incorporate analysis of variation in phase difference. If a sequence is confined, the response to a pressure increase is instantaneous [Rasmussen and Crawford, 1997]. In compliance with the compressible storage theory (stress balance) which leads to equations (2)–(5), any change in the total stress is shared between the matrix and the pore fluid [Domenico and Schwartz, 1998]. Consequently, an increase in loading on a confined system such as imposed through atmospheric pressure rise results in an increased total stress. This increases the pressure in the formation which is now higher than that in the borehole and therefore leads to an increase in observed water level.

Since atmospheric loading effects are uniform, lateral flow is negligible if the formation has a sufficient extent (under undrained conditions) [Cutillo and Bredehoeft, 2011]. Cyclic loading from atmospheric pressure...
pressure must therefore induce a 180° (or π radians) phase difference between the atmospheric oscillations and the hydraulic head response. Acworth et al. [2016a] noted that the phase difference at the frequency of 2 cpd can be evaluated and used to identify confined conditions using atmospheric pressure and hydraulic head time series only.

In this paper, we use the method developed by Acworth et al. [2016a] to calculate the formation’s BE in situ at discrete points over depth (i.e., 1 m long screen locations set in a gravel pack and sealed with grout) using the response of hydraulic heads to atmospheric tides. As hydraulic head oscillations at 2 cpd frequency are affected by both atmospheric and Earth tides, the Earth tide influence must be removed to reveal the atmospheric tide.

The amplitude and phase of the atmospheric tide component at 2 cpd can be quantified from field measurements of atmospheric pressure which are often readily available (e.g., weather station or barometric logger). The Earth tide impact on groundwater heads can be quantified using a synthetic gravity record created through TSoft [Van Camp and Vauterin, 2005]. Using this in combination with hydraulic heads, the amplitudes of Earth tide and groundwater response can be calculated at a nearby frequency that is unaffected by atmospheric pressure, e.g., at 1.9324 cpd (M2). The relative impact on the groundwater must be the same for the 2 cpd frequency of interest and the amplitude can therefore be inferred from the synthesized Earth tide record at 2 cpd frequency. Since tides are harmonic signals, their individual contributions (amplitudes) at 2 cpd can be disentangled using the Harmonic Addition Theorem once their respective amplitudes and phases are established.

To remove the influence of the Earth tide from hydraulic heads, the calculation can be made directly in the frequency domain at 2 cpd. The equation is given by Acworth et al. [2016a] as

\[ BE = \frac{S_{GW}^2 + S_{ET}^2 \cos(\Delta \phi) M_{GW}^2}{S_{ET}^2}, \]  

where \( S_{GW}^2 \) is the amplitude of the hydraulic head, \( S_{ET}^2 \) is the amplitude of the earth tide, and \( S_{ET}^2 \) the amplitude of the atmospheric tide; \( \Delta \phi \) is the phase difference between the Earth tide and atmospheric drivers (all at 2 cpd frequency); and \( M_{GW}^2 \) is the amplitude of the hydraulic head and \( M_{ET}^2 \) the amplitude of Earth tides at 1.9324 cpd frequency.

### 2.5. Estimation of the Loading Efficiency Using the Hydraulic Head Response to Rainfall

Equation (2) illustrates that in a sequence with a very low BE, the loading efficiency must be near unity, i.e., \( \gamma \approx 1 \). The impact of a change in stress at the surface, for example, caused by the mass of received rainfall, should be instantaneously propagated downward with a close match between the mass of rainfall received and the rise in height of the hydraulic head. Analogously, a decrease in weight caused by evaporation from soil cracks or from evapotranspiration by growing crops will also be reflected as a decrease in hydraulic head.

We exploit this loading phenomenon, referred to as weighing lysimeter [Rasmussen and Mote, 2007], to calculate the loading efficiency (\( \gamma \)). We manually extract the magnitude of the hydraulic head response to the cumulative amount of rainfall at the surface. Here rainfall events are defined as periods of time where rainfall was recorded without significant breaks. Pairs of rainfall data, formed from the sum of the event-based rainfall and the rise in hydraulic head, were correlated using

\[ \Delta h_p = \gamma \cdot P_e, \]  

where \( \Delta h_p \) is the hydraulic head response (m) as a result of the total event-based rainfall \( P_e \) (m). The linear relationship is constrained to pass through the origin. Runoff is assumed to be zero which is reasonable on this very flat surface. Evapotranspiration is also assumed to be negligible during periods of rainfall. It is important to note that this rainfall event-based \( \gamma \) calculation was carried out independently from the previously described BE quantification.

### 2.6. Frequency Domain Calculations

The Discrete Fourier Transform (DFT) can be applied to hydraulic head data in order to decompose the time series into a finite sum of sinusoidal components, with varying amplitudes and phases for each frequency
component. This can be carried out through the Fast Fourier Transform (FFT) in programming environments such as MATLAB®, R, Python, or the software package TSoft [Van Camp and Vauterin, 2005]. A frequency domain band-pass filter is used to identify the relative strengths of components in the hydraulic head data associated with a particular frequency. We investigate the energy at a frequency, \( f_0 \), of 2 cpd (12 h period) using a bandwidth, \( f_w \), of 0.02 cpd centered on 2 cpd for much of what follows. The transfer function has a value of \( 1 - 2 \left( \frac{f - f_0}{f_w} \right)^2 + \left( \frac{f - f_0}{f_w} \right)^4 \) in the range \([f_0 - f_w, f_0 + f_w]\) and is 0 elsewhere [Van Camp and Vauterin, 2005]. As the principal solar semidiurnal (\( S_2 \)) component occurs at exactly 2 cpd, this treatment allows for the \( S_2 \) signal to be subsequently viewed in the time domain as a sinusoid with varying amplitude and phase representing the specific part of the atmospheric pressure or hydraulic head at that frequency alone.

There are various methods to display the data associated with a single frequency. The signals from all the piezometers can be compared as simple plots of amplitude against time. In addition, Van Camp and Vauterin [2005] proposed a phase map where the amplitude variation over one cycle (here 12 h) is unwrapped and tabulated. Values for the next cycle are similarly unwrapped and placed into an adjacent column with the process repeated until the end of the data time period is reached. This data can then be shown as a color plot. The \( y \) axis represents time; the \( x \) axis represents phase between 0 and 1 (or 0° and 360°), while the amplitude of the signal can be expressed by a color map extending from \( \min[a] < a < \max[a] \), where \( a \) is the amplitude. The phase map visualizes the variation in amplitude over phase and time.

To reveal the state of groundwater confinement, the phases of the hydraulic head oscillations at 2 cpd (\( \phi \)) were also evaluated using FFT applied to windowed sections of the data. Shorter duration hydraulic head time series may be affected by rapid, transient changes to hydraulic conditions (i.e., through precipitation events) while longer windows result in poorer temporal resolution, thus a compromise must be made when attempting to resolve transient changes to amplitude and phase behavior owing to the uncertainty principle inherent to the DFT [Havin and Jörnicke, 1994].

3. Results

3.1. Hydraulic Heads, Atmospheric Pressure, and Rainfall Data

The hydraulic head data monitored at Cattle Lane are shown in Figure 3. The responses in all piezometers are broadly similar with declining heads between January and June during the Southern Hemisphere summer and autumn. There is also a general increase in hydraulic head with depth. Acworth et al. [2015a] reported that the highest fluid conductivity occurs at 10 m depth with steadily reducing values to the basement. The hydraulic head responses can be subdivided into three groups:

1. Piezometers at CL-5 and CL-10 m show a different response starting in June 2016 with a recovery that is far more marked than that in the deeper piezometers.
2. Piezometers at CL-15 to CL-35 m have broadly similar responses although they also exhibit a longer (days) phase lag in their response to rainfall.
3. The piezometer at CL-40 m depth and borehole GW 30061 have a higher hydraulic head and have a slightly greater amplitude response to the rainfall events shown.

It is noticeable that all hydraulic heads respond instantaneously to rainfall at the surface.

3.2. Barometric Efficiency Over Depth

The barometric efficiency (\( BE \)) values for the depth profile of piezometers, as calculated using equation (6), are summarized in Table 1 and plotted in Figure 4. Values show very low barometric efficiency increasing steadily from 0.01 at 5 m depth to 0.138 at 38 m depth. According to these values, the loading efficiency must be near unity.

3.3. Loading Efficiency Over Depth

Loading efficiency (\( \gamma \)) is calculated using equation (3). The response of the middle group piezometer CL-35 to rainfall (total of nine analyzed events) is shown in Figure 5. A regression plot of the change in hydraulic head against the rainfall is shown as an inset. The straight line correlation as calculated from the rainfall events according to equation (3) results in a loading efficiency of \( \gamma = 0.98 \) (\( R^2 = 0.97 \)). While the rainfall station is 3.8 km distant from the site, the data are sufficiently representative and show a clear response. This
is in good agreement with the value of $\gamma$ predicted by equation (2) when using the barometric efficiency values calculated earlier. More rainfall events could be included but the overall relationship is not in doubt based on these results. 

There is a steady decrease in head between rainfall events which is an indication of weight loss at the surface due to evapotranspiration. A straight line approximation for the autumn period (May in Figure 5) has a slope of 2.14 mm/d. Theoretical evaporation for May 2016 at the Paringa weather station (Figure 1) using the Penman-Monteith formula [Allen et al., 1998] was 1.68 mm/d (T. Bernardi, NSW DPI, personal communication, 18 October 2016). Given that the Paringa location is at a higher elevation (~ 50 m) and close to trees, whereas the Cattle Lane location is on flat farming land (Figure 1a), the agreement between the estimated value at Paringa and the measured value at Cattle Lane is very good.

Table 1. Name of Piezometer or Bore, Barometric Efficiency, Total Moisture Derived From the Core, Specific Storage Estimates Based Upon Total Moisture Measurements Quantified Using Equation (5) (Column 4) and Then Repeated Based Upon Estimates of Specific Yield Rather Than Total Moisture Content (Column 6)

<table>
<thead>
<tr>
<th>Piezo/Bore</th>
<th>Barometric Efficiency</th>
<th>Total Moisture $\theta$</th>
<th>Specific Storage $S_s$</th>
<th>Effective Moisture $S_{es}$</th>
<th>Specific Storage $S_{es}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL-5</td>
<td>0.010</td>
<td>0.38</td>
<td>$1.67 \times 10^{-4}$</td>
<td>0.05</td>
<td>$2.20 \times 10^{-5}$</td>
</tr>
<tr>
<td>CL-10</td>
<td>0.007</td>
<td>0.50</td>
<td>$3.16 \times 10^{-4}$</td>
<td>0.02</td>
<td>$1.26 \times 10^{-5}$</td>
</tr>
<tr>
<td>CL-15</td>
<td>0.032</td>
<td>0.55</td>
<td>$7.76 \times 10^{-5}$</td>
<td>0.08</td>
<td>$1.06 \times 10^{-5}$</td>
</tr>
<tr>
<td>CL-20</td>
<td>0.039</td>
<td>0.52</td>
<td>$6.06 \times 10^{-5}$</td>
<td>0.02</td>
<td>$2.12 \times 10^{-6}$</td>
</tr>
<tr>
<td>CL-25</td>
<td>0.042</td>
<td>0.50</td>
<td>$5.31 \times 10^{-5}$</td>
<td>0.02</td>
<td>$2.12 \times 10^{-6}$</td>
</tr>
<tr>
<td>CL-30</td>
<td>0.042</td>
<td>0.45</td>
<td>$4.83 \times 10^{-5}$</td>
<td>0.02</td>
<td>$2.15 \times 10^{-6}$</td>
</tr>
<tr>
<td>CL-35</td>
<td>0.059</td>
<td>0.10</td>
<td>$7.61 \times 10^{-6}$</td>
<td>0.01</td>
<td>$7.61 \times 10^{-6}$</td>
</tr>
<tr>
<td>CL-40</td>
<td>0.121</td>
<td>0.20</td>
<td>$7.42 \times 10^{-6}$</td>
<td>0.20</td>
<td>$7.42 \times 10^{-6}$</td>
</tr>
<tr>
<td>GW 30061</td>
<td>0.138</td>
<td>0.20</td>
<td>$6.50 \times 10^{-6}$</td>
<td>0.20</td>
<td>$6.50 \times 10^{-6}$</td>
</tr>
</tbody>
</table>
3.4. Phase Difference Between Atmospheric Pressure and Hydraulic Heads at 2 cpd Frequency

A depth profile showing the phase difference of the 2 cpd component in hydraulic heads and atmospheric pressure is plotted in Figure 4b. The phase coherence between the piezometers below 10 m is also shown in Figure 6. The data cover a 3 day time period so that detail is clearly observable. Note the greater ampli-
tude for P40 and Borehole GW 30061 and the similarity of all the remaining piezometers (CL-15 to CL-35). The 180° phase difference between atmospheric pressure and the groundwater levels is clearly apparent.

Figure 7 shows the phase maps of the barometric pressure component at 2 cpd along with the records for each of the piezometers (CL-5 to CL-40) and borehole GW 30061. While the phases for the deepest and the shallow most piezometers are 180° shifted but constant over time, CL-5 and CL-10 illustrate a clear variability.

Figure 8 shows the amplitude ratio and the phase difference of the 2 cpd component in hydraulic heads, measured in the four uppermost piezometers, and the atmospheric pressure over time as calculated using a rolling window to the time series. It is evident that the phase difference is stable for the deeper piezometers, whereas it varies over time for the shallower observation points. Clear phase jumps are visible at points in time which seems related to rainfall at the surface.

4. Discussion

4.1. A Vertical Profile of Groundwater Storage Properties

Figure 2 shows the sediment properties of the vertical sequence, geophysical logs (bulk electrical conductivity), and comments on the lithology. These data, previously established by Acworth et al. [2015a], provide important context to the present discussion.

When calculating specific storage from equation (5) a porosity estimate is required. The question arises as to which measure of porosity is appropriate to use, i.e., total or effective. In the first part of Table 1 (columns 3 and 4), the value of moisture content derived from the nearest core measurements is used in...
equation (5) with $BE$ estimates from Table 1 to estimate specific storage. These data represent a minimum value for specific storage as the total moisture content is the highest possible value for $\theta$.

In reality, the majority of the core was dry when drilled with very little effective porosity (equal to specific yield) that could contribute to water moving in response to a change in atmospheric pressure. Robson [1993] notes that in clayey materials, the effective porosity is almost zero with the specific yield only slightly greater. In smectite-dominated clay, the majority of the water content is adsorbed onto and into the crystalline clay matrix and is not available to drain out. It is bound to the clay crystal matrix and held at a higher density than free water [Galperin et al., 1993]. The base of the core contained higher sand content (Figure 2) and a value of specific yield of 0.2 has been used for these samples. The moisture content for the nearest core sample and the specific storage calculated using this value are shown in Table 1 (columns 5 and 6) for comparison. The values for piezometers CL-35, CL-40, and bore hole GW30061 are estimates as the core drilling stopped at 31 m depth.

The specific storage estimates generated using an estimated effective moisture are an order of magnitude smaller than values calculated using the total moisture content. In the limit that the effective moisture is zero, the specific storage will also be zero.

The simultaneous increase in hydraulic head at all depths after rainfall events illustrates that the system is loaded by the weight of water received at the surface. The fact that the hydraulic head increases correlates well with the amount of rainfall at the surface (Figure 5) confirms that these sediments between 15 and 35 m act as a weighing lysimeter [Rasmussen and Crawford, 1997; Rasmussen and Mote, 2007]. This observation is significant as a simple inspection of the hydraulic head record could lead to the interpretation that

---

**Figure 5.** Piezometer CL-35 responds to rainfall events as a weighing lysimeter. Rainfall event numbers refer to the symbols in the regression plot. The green dashed line represents the declining trend due to evapotranspiration.
Groundwater recharge is responsible for the head increases. Such an interpretation would be supported by the age of the sediments and that they are clearly unconsolidated. However, this is shown to be incorrect by the confined nature of the sediments (see below), and the fact that the shallow bulk electrical conductivity indicated by the geophysical logs (Figure 2) is so elevated.

Earlier work by Timms and Acworth [2005] using the amplitude decay and phase lag caused by major rainfall events over a 4 year period produced a BE result of 0.07, which is broadly similar for the integrated clay sequence from the surface to 35 m depth. The phase lag between the surface response to rainfall and the response at the base of the clay varied between 49 and 72 days.

Several strands of evidence point to a significant lithological change which is confirmed to be a sandy silt layer between 11.5 and 13.5 m depth (Figure 2). This depth corresponds to an age of between 40 and 60 ka [Acworth et al., 2015a] which was identified from the core analyses as being very fine sand in a clay matrix (Figure 2) and also has a reduced bulk electrical conductivity. This layer was incompetent when drilled and required casing to support it. The hydraulic head and phase data (Figure 6) indicate that all the material below this depth (10–15 m) responds as a confined aquifer. The high loading efficiency ($c$) values are reflected in the fact that the sequence operates as a weighing lysimeter (Figure 5).

4.2. Change in State of Confinement Determined From the Phase Difference Between Atmospheric Pressure and Hydraulic Heads at 2 cpd Frequency

Acworth et al. [2016a] previously mentioned that a 180° phase difference between atmospheric pressure and hydraulic heads at 2 cpd frequency indicates groundwater confinement. It is evident that there is a change in the phase difference over depth when the data series is analyzed in the frequency domain (Figure 4b), and that there are confined conditions with confined storage values below ~10 m. It is important to note that values are an average for the duration of the record to which the Fourier transform is applied.

In Figure 4b, the shallowest piezometers show a phase difference that is different to that seen in deeper locations. To evaluate the influence of time variability, the windowed phase evaluation in Figure 8 can be used. This shows that the phase difference for CL-5 and CL-10 changes between an unconfined response
where the phase is the same as the atmospheric pressure, to a confined response where the phase is 180°
different and indicative of confined conditions [Acworth et al., 2016a].

Another way of presenting this data is seen in Figure 7, where the change of phase with time is
clearly represented. The three group responses (CL-5 and CL-10, CL-15 to CL-35 and CL-40 GW 30061)
are again evident. CL-5 and CL-10 show major changes in phase difference over time. CL-40 and GW
30061 have almost identical phase maps. The intervening piezometers (CL-15 to CL-35) have the
same basic shape but with subtle differences in shape on the phase map. While it is not clear exactly
what these relate to we hypothesis that it is caused by the smaller amplitudes resulting in more noisy
phase data.

Experimental work on similar clays taken from a field on the Liverpool Plains has shown that, despite the
fact that the soils become deeply cracked during dry weather, they do not become freely draining until the
soil becomes saturated [A. Greve et al., 2010]. This counter-intuitive result explains the observed phase
phenomena. After rain, the extent of water saturation close to the surface and the associated clay expansion
may well provide a confining layer, albeit with trapped air deeper in the profile for some time. This leads to
the hydraulic head oscillations at 2 cpd frequency responding in a confined manner with a phase difference
between the atmospheric pressure of 180°.

The change in confinement, expressed as a change in phase in response to a rainfall event, is shown in Fig-
ure 8. While rapid, transient changes induced by rainfall events can result in spurious phase behavior in DFT
calculations due to spectral leakage from signal nonstationarity [Rau et al., 2015], the overall trend toward
confined phase behavior is evident in the period starting around 1 June 2016. Our results demonstrate that
the phase difference between atmospheric pressure and hydraulic heads at 2 cpd frequency can be used to determine spatiotemporal changes in groundwater confinement.

**4.3. Implications for Groundwater Resource Analysis**

Our results provide information on recharge processes in the smectite-dominated clays that develop deep cracks during dry periods [A. K. Greve et al., 2010; A. Greve et al., 2010] and which allow significant evaporation from the soil profile [Adams and Hanks, 1964]. Rainfall is seen to be rapidly absorbed into the sides of cracks and adsorbed onto the clay rather than recharge passing through the clay to a water table aquifer [Timms et al., 2001] and cracks close rapidly. Where a downward hydraulic gradient exists, the profile becomes draining only once the soil is completely saturated, as noted in laboratory weighing lysimeter tests reported by A. Greve et al. [2010].

The lack of vertical movement of groundwater through these deposits explains the continued presence of high salinity in the upper 10 m which is assessed to be crystalline salt dusts mixed with silt, blown in during arid times associated with the last glacial epoch [Acworth et al., 2015a]. Peaks in bulk electrical conductivity and silt content seen in Figure 2 at 2, 5.5, and 8.5 m would correspond with ages of 7, 21, and 32 ka, respectively [Acworth et al., 2015a].

Deeper parts of the system act as a field weighing lysimeter [Bardsley and Campbell, 1994] with instantaneous hydraulic head rises in response to rainfall indicating a change in weight at the surface. Evapotranspiration loss causes a decrease in weight and a corresponding relaxation of the confined aquifer hydraulic heads underneath.

Specific storage values that are a function of the volume of water (effective moisture) that is free to respond to the change in atmospheric pressure can be determined using this approach. The volume is indicative of the unbound water in the system, i.e., very low in clays and higher in sand or gravel horizons. This is a similar concept to that of specific yield; however, the term specific yield is normally reserved to describe water that drains under gravity from an unconfined system [Domenico and Schwartz, 1998].

---

**Figure 8.** (a) Hydraulic head from (right) selected boreholes and (left) daily rainfall. (b) Relative amplitude of the $S_2$ component of the groundwater levels and atmospheric pressure, evaluated with a centered 15 day window. (c) Relative phase difference of the $S_2$ component of the groundwater levels compared to that of the atmospheric pressure, evaluated with a centered 15 day window. Here the phase has been restricted to $[-360^\circ, 0^\circ]$ for ease of interpretation. The $S_2$ signals in the shallow boreholes (P5 and P10) show a clear response to precipitation after a relatively dry period, indicating increased confinement.
In this paper, we used an independent approach to verify that atmospheric tides can be used as a natural tracer to calculate accurate storage properties along a sequence of sediments without the efforts inherent to pumping test. This approach only requires relatively short ($\geq 15$ days) but continuous records of atmospheric pressure and hydraulic heads as well as porosity estimates [Acworth et al., 2016a]. The latter should be available as part of a routine evaluation of the materials obtained during drilling.

Our results illustrate that using the 2 cpd atmospheric components in hydraulic heads provides a convenient approach to calculate BE and compressible storage properties over depth and to determine changes in confinement over space and time. For a more complete analysis of groundwater systems, we recommend to apply our new approach alongside other methods that calculate aquifer properties using the response of hydraulic heads to Earth tides [Cutillo and Bredehoeft, 2011; Burbey et al., 2012; Allègre et al., 2016].

It may be appropriate to refer to periods of time when the phase is intermediate between unconfined and confined as representing a zone of semiconfinement. If so, it must be recognized that the term “semiconfined” may not be a permanent descriptor but one which can change over space and time. The specific storage in this zone is an order of magnitude greater than in the confined material below but still very much smaller than for truly unconfined conditions. Our results demonstrate that atmospheric tides can be used as a natural tracer to significantly improve the spatiotemporal characteristics and conceptual understanding of a groundwater system.

5. Conclusions

In this paper, we exploit the hydraulic head response to atmospheric tides at 2 cpd frequency as a tracer to calculate a depth profile of barometric efficiency and compressible groundwater storage of the confined zone. We illustrate this approach using atmospheric pressure data and hydraulic heads recorded at a site with piezometers screened at discrete depths between 5 and 55 m across a sequence of sediments where the lithological depth profile is well defined from sediment core analysis. The results are verified through loading efficiencies calculated at the respective depths from the hydraulic head response to rainfall at the surface.

Previous work suggested that the phase difference of the atmospheric tide component at 2 cpd frequency, calculated in the frequency domain using the Fourier transform of the atmospheric pressure and hydraulic heads, is $180^\circ$ when the groundwater is confined. We expand on this work by applying a moving window to demonstrate that this phase difference in the shallower subsurface can be time variable. Consequently, this phase difference can be used to determine spatiotemporal changes in confinement and to delineate and characterize the semiconfined zone.

At our field site, the depth variation in BE and the associated change in phase of the 2 cpd component embedded in the hydraulic head are interpreted in terms of a conceptual model for the smectite clay-dominated sediments. An upper sequence of $\sim 10$ m exists where deep cracking and drying can occur and that can change between confined and unconfined conditions. Using simple assumptions concerning probable free water content, a profile of specific storage can be derived for the sequence of sediments.

It is clear from our results that the term “semiconfined” needs to be understood as a time-varying descriptor covering the zone between fully confined and unconfined. Conditions in the shallow unconfined zone could be labeled as a semiconfined zone where the hydraulic head may vary between confined and unconfined as rainfall recharge impacts the properties of the clay. Deep cracking and evaporation from the sides of the cracks, combined with evapotranspiration can reestablish unconfined conditions. This is perhaps particularly the case in smectite-dominated soil systems.

The hydraulic head response to the 2 cpd component of the atmospheric tide is a natural tracer that can better define the hydraulics of any groundwater system but especially deep sedimentary basins. Our new approach provides a simple but powerful tool to develop significantly improved conceptual groundwater models that much better represent the field conditions.
Acknowledgments

The data used in this analysis were collected with equipment provided by the Australian Federal Government financed National Collaborative Research Infrastructure Scheme (NCRIS), an Australian Government initiative supported by the Australian National Water Commission (NCGRT), an Australian Government initiative supported by the Australian Government Research Infrastructure Scheme (NCRIS) and the National Collaborative Water Resources Research Acceleration and Attraction Program (RAAP) in 2016. Dayna McGeeney from the UNSW Water Research Laboratory undertook the PSD and soil moisture analyses.

References


Rasmussen, T. C., and T. L. Mote (2001), Monitoring surface and subsurface water storage using confined aquifer water levels at the Savannah River Site, USA, Vadose Zone J., 6(2), 327, doi:10.2136/vzj2006.0049.


