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Understanding connected surfacewater/groundwater systems using Fourier analysis of daily and sub-daily head fluctuations

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- 1 Understanding connected surface-water/groundwater systems using Fourier
- 2 analysis of daily and sub-daily head fluctuations
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- 13 Abstract

14 The long-term monitoring records of hydraulic heads frequently contain fluctuations 15 originating from different cyclic drivers. Fourier analysis applied to these records can 16 reveal connected surface-water/groundwater system characteristics. The various 17 components of the atmospheric tides, the earth tides and the presence of diurnal 18 responses to evapotranspiration are identified and isolated through band-pass filtering of 19 data recorded from both vented and absolute gauge transducers. The signature of the 20 different cyclic drivers is contained in amplitude and phase of the various signal 21 components and can be used to determine the degree of system confinement. A 22 methodology is described for the calculation of barometric efficiency in confined aquifers 23 based upon the amplitude of the M_2 and S_2 components of the earth and atmospheric 24 tides. It is demonstrated that Fourier analysis of water-level fluctuations is a simple but 25 underused tool that can help to characterise shallow groundwater systems.

26

- 27 Keywords: Australia, Analytical solutions, Confining units, Groundwater/surface-water
- 28 relations, Groundwater hydraulics
- 29

30 **1.** Introduction

31 Signal analysis techniques are routinely used in many areas of the earth sciences (Davis, 32 1973) with sophisticated packages in use in the geophysics industry or the area of 33 coastal engineering (Doodson, 1921; Emery & Thompson, 2004). Despite early work in 34 the groundwater field by Weeks (1979), van der Kamp and Gale (1983), Hsieh et al, 35 (1987), Rojstaczer (1988a, 1988b), Rojstaczer and Agnew (1989), Rojstaczer and Riley 36 (1990), for example, and the regular use of signal analysis techniques in other disciplines, 37 there is little evidence of their routine use in hydrogeological studies. This is unfortunate 38 as this early work demonstrated that signal analysis could be used to derive a much 39 improved understanding of the impacts of mechanical loading of confined aquifers and to 40 the determination of barometric efficiency and specific storage. Where signal analysis 41 techniques have been used in hydrogeology (for example Weeks (1979), Hsieh et al, 42 (1987) or Merritt (2004)), the analysis has been for either deep confined or deep 43 unconfined aquifer systems. Work in shallow connected surface water groundwater 44 systems has concentrated on the diurnal variation in water level that could be related to 45 evapotranspiration effects (Gribovszki et al 2010; Johnson et al, 2013).

46 The measurement of water levels for hydrogeological investigations is often considered a 47 trivial task but needs to be undertaken carefully if the full range of important information 48 contained in the data set is to be sensibly extracted (Post & von Asmuth, 2013). Where 49 absolute gauge measurements (transducer diaphragm sealed on the reference side to a 50 vacuum or a fixed pressure) are made with a transducer suspended at a fixed depth in 51 the bore/piezometer, the logger records the total pressure on the transducer diaphragm. 52 This includes the pressure of the water column above the point of measurement and the 53 pressure of the overlying air. In simple terms, if the overlying air pressure can be 54 measured by another logger separately, it can be separated from the pressure exerted by 55 the height of the water column and removed by subtraction. This is the recommended

approach of many manufacturers of absolute pressure gauge transducers sold into the groundwater market. The accuracy of the derived water pressure measurement is therefore directly related to the accuracy of the atmospheric pressure measurement and simultaneous measurements are essential. It is the necessity to accurately measure the atmospheric pressure variation that has prompted our revised interest in the causes of the daily and sub-daily head fluctuations caused by atmospheric pressure variation and what we can learn about the aquifer system by observing this response.

Price (2009) has demonstrated that the data derived from the correct use of absolute gauge transducers are the same as that obtained for vented gauge transducers, as long as the system accuracy is sufficient. A vented gauge transducer makes the correction for atmospheric pressure automatically by subjecting the opposite side of the transducer diaphragm to atmospheric pressure via the use of a thin pipe extending from the transducer to the atmosphere (Price, 2009). Sorensen and Butcher (2010, 2011) give an extensive review of the accuracy of available logging systems.

70 In this paper we use signal analysis techniques based on the Discrete Fourier Transform 71 (DFT) on a long sequence (35,000 data points with 96 measurements per day) of 72 groundwater data from a connected surface water - groundwater environment at Maules 73 Creek in Northern New South Wales, Australia. Results are presented from a stream 74 gauge (vented transducer), loggers in two unconfined piezometers and a logger in a 75 confined piezometer (absolute gauge transducers). We describe applications of Fourier 76 signal analysis techniques to both vented and absolute gauge data and demonstrate how 77 the use of this approach can assist with hydrogeological interpretation of long data series 78 from a shallow groundwater environment connected to a stream. In particular, we show 79 how the use of a DFT pair, where the time series data is shown alongside the frequency 80 spectrum, can also be used to detect Earth tides (indicating a confined aquifer response) 81 and calculate the barometric efficiency of an aquifer, or to detect the presence of 82 evapotranspiration in a riparian zone.

83 2. Methodology

84 **2.1. Catchment Description**

A site on Maules Creek in Northern New South Wales, Australia (Latitude: -30.5°, Longitude: 150.08°, Elevation 253 m Australian Height Datum (AHD)), is used to demonstrate the use of the DFT pair in this study. The site has been described in previous papers (Andersen and Acworth, 2009; Rau et al., 2010; McCallum et al, 2013) and only background data will be repeated here.

90 Figure 1

91 Maules Creek is a tributary to the Namoi River that drains into the Darling River and is a 92 part of the Murray-Darling River Basin. The creek is largely ephemeral, but has a 93 perennial section in its middle reach at Elfin Crossing (Fig. 1) that is fed by groundwater 94 discharge from a shallow coarse grained aquifer. At low-flow conditions, the surface-95 water flow in Maules Creek at this middle reach is exclusively controlled by surface-96 water/groundwater interactions (Andersen and Acworth, 2009), since the reaches above 97 and below dry out except when the creek is in flood. There is a permanent flow gauge at 98 Elfin Crossing that was established by the NSW Government with real-time data available 99 on the web (Waterinfo, 2013). The water level at this gauging station is recorded using a 100 vented transducer with a cable running from the pool and buried in the bank up to the 101 gauging station hut. Details and pictures can be seen on the web site. Low flow discharge 102 from this gauge is reported to be below approximately 10 ML/day (115 L/s).

A climate station is installed at a site at Bellevue Farm, some 11 km due west from Elfin
Crossing where temperature, incoming solar radiation, wind and rainfall are measured
amongst other parameters (Fig. 1).

Shallow piezometers were installed in a wooded area to the east of the creek (e.g. EC 17 on Fig. 2) using a Geoprobe pneumatic hammer to drive casing through the coarse alluvium. This method met refusal at a few metres depth. A large rotary rig equipped with a 300 mm combination percussion air-hammer and casing advance system (TUBEX) was used to achieve greater penetration on the west bank and boreholes BH 7 and BH 12

(Fig. 2) were completed, each with multiple piezometers installed isolated by a cement seal. Drill records (BH 12) indicate a sequence of sandy gravels with some clay to a depth of approximately 17 m. A clay layer is present between 25 and 30 m depth which has a significant impact on hydraulic heads with a consistent reduction in head (i.e. downward gradient) of approximately 1.25 m. Details of the piezometers and boreholes for which water level records are presented are given in Table 1.

117 The banks of the creek are lined with mature River Red Gums (Eucalyptus 118 camaldulensis) that often have their trunks standing in surface water. The lower part of 119 the catchment between Elfin Crossing and the junction with the Namoi River is 120 extensively flood irrigated using a combination of groundwater abstraction from deeper 121 parts of the alluvial aquifer and Namoi River water (Andersen and Acworth, 2009). Except 122 under flood conditions, surface flow in Maules Creek ceases at some point between Elfin 123 Crossing and the Namoi River as a result of losses to the underlying aguifer. The location 124 of this cease to flow point can rapidly move upstream as a response to the start of 125 groundwater abstraction and flow conditions at Elfin Crossing appear to be permanently 126 impacted with significant downward gradients beneath the pool at Elfin Crossing (Rau et 127 al., 2010) as noted above. The alluvial material that forms the base to the river channel 128 has been cut into Permian coal measures (Maules Creek Formation) that are under 129 active exploration by mining companies.

130	Figure 2		
		_	

131

132 **Table 1**

133 **2.2. Water level measurement**

In this paper we use water levels that were recorded with a combination of vented and unvented (absolute pressure) loggers. Absolute gauge transducers (Solinst Levelogger Gold and Edge) were used at EC 17, BH 12.2 and BH 7.1 Atmospheric pressure was measured using a Solinst Barologger installed at 2 m below ground level and above the water level in BH 8 (Fig. 2). We recorded water levels with a time resolution of 96 cycles per day (cpd) corresponding to 15 minute time intervals so that linkages between the surface stream (flood response) and the groundwater system could be accurately resolved.

142 **2.3. The Discrete Fourier Transform (DFT)**

The DFT of a long set of regularly spaced data, such as that provided by data logging of a groundwater level at a regular time interval, can be expressed in the frequency domain as a sequence of individual sinusoids (Fourier, 1822) that collectively add to make up the original signal. The mathematical expression of the DFT is as follows (e.g. Smith, 2007):

147
$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-i2\pi \frac{kn}{N}}, \qquad \qquad \text{Equation 1}$$

where: X(k) is the frequency spectrum corresponding to the time series x(n),. In other words, Eqn. 1 transfers data from the time domain (where it is a series of measurements of a given parameter made at a constant time interval) to the frequency domain (where it can be represented by a plot of frequencies against the amplitude of that frequency). The Inverse Discrete Fourier Transform (IDFT), where data can be transferred from the frequency domain to the time domain, is defined as (e.g. Smith, 2007):

154
$$x(n) = \frac{1}{N} \sum_{k=0}^{N-1} X(k) e^{-i2\pi \frac{kn}{N}}$$
. Equation 2

For a detailed discussion of the DFT and its mathematical properties the reader is referred to Oppenheim and Schafer (1999), Emery & Thomson (2004) or Smith (2007). The graphical representation of data in both the time domain and the frequency domain can be referred to as a DFT pair (see Fig. 3 for an example).

159 It is noteworthy that the resolution in the frequency domain is directly linked to the 160 resolution in the time domain, i.e. the sampling frequency of water levels. The mapping of 161 higher frequencies is therefore limited by the sampling rate in the time domain, as the 162 correct identification of any particular sinusoidal component requires at least 2 samples 163 within one period. The latter is referred to as the Nyquist frequency (f_N) expressed as:

164
$$f_N = \frac{1}{zM} = \frac{f_2}{z}$$
, Equation 3

where: Δt is the sampling time interval, or f_{s} is the sampling frequency. It is important to acknowledge that any energy from signal components with frequencies higher than that will be contained (aliased) in the spectrum but cannot be identified separately.

168 The selection of a water level sampling frequency is therefore an important consideration 169 and forms a compromise between the requirements for measuring rapid water level 170 variations and available resources for data transmission, storage and manipulations.

171 **2.4. Fourier analysis and filtering**

The DFT (Eqns. 1-2) is a fundamental component of many signal processing software packages. It is commonly implemented as an algorithm called the Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT) which efficiently solve the DFT (Eqn. 1) and IDFT (Eqn. 2) numerically. Examples for popular software packages particularly suited to signal processing are Matlab, Mathematica (commercial), R, Octave and PyLab (open source).

178 In this paper we work with the software package TSoft (Van Camp and Vauterin, 2005). 179 TSoft is free software available for the Windows operating systems (TSoft, 2013). The 180 package allows the application of a variety of filters, including those based on the Fourier 181 Transform, and provides excellent graphical applications for data display. The results of 182 data logging can be saved as a text file and imported into TSoft using the free format 183 specifier (TSoft, 2103). It is assumed that the data is regularly sampled in time and the 184 user is prompted for a start date and time and the sample interval (s) upon data import. 185 For more details refer to the TSoft manual available online.

An example of Fourier analysis using the DFT on water levels is illustrated in Fig. 3 where 3 typical frequencies found in groundwater monitoring, viz, a signal repeating at 2 cycles per day (12 hour period), 1 cycle per day (24 hour period) and at 0.2 cycles per day (5 day period) can be added together to show a sequence often seen in atmospheric pressure data. Here, the 5 day variation represents the somewhat variable mesoscale

191 pressure variation typical for the movement of low pressure systems. This example also 192 illustrates the linearity of the DFT whereby no information is lost in the transform 193 calculation between the time domain and the frequency domain. An excellent example of 194 the use of signal processing is given by Hsieh et al (1987).

195 Figure 3

196 The frequency domain is particularly useful for data manipulation, as it allows the 197 extraction of a signal with a certain frequency that can be unclear in the time domain 198 data. This process is referred to as filtering. Undesired frequencies can be removed by 199 applying a weighting function to the data in the frequency domain. Three common filters 200 are available; low pass, high pass and band-pass functions. The first two only allow the 201 lower and the higher frequencies beyond a desired 'cut-off' value to pass when the signal 202 is transformed back into the time domain. The latter removes both lower and higher 203 frequencies and requires an additional bandwidth parameter defining the width of the 204 frequency window (on either side of the cut-off). Acworth and Brain (2008) illustrated the 205 use of these filters in their study of groundwater levels in shallow granites. In this paper, 206 we apply a band-pass FFT implemented in TSoft in order to investigate the phase and 207 amplitude of various frequencies at 1cpd or greater representing atmospheric tides, Earth 208 tides or other processes. The FFT uses a windowing technique to allow the variation in 209 amplitude of a specific frequency throughout the complete signal. One side effect of the 210 bandpass filtering is the edge effect introduced at the beginning and the end of the 211 filtered time series.

212 3. RESULTS AND INTERPRETATION

213 **3.1. Atmospheric Pressure**

- A DFT pair of atmospheric data for a 9 month period sampled every 15 minutes (96 cpd)
- is shown in Fig. 4.

Figure 4

The complete frequency spectrum of the recorded atmospheric pressure is shown with data up to 48 cpd (the Nyquist frequency for logging at 96 cpd), although there is very little energy for frequencies greater than 3 cpd (8 hourly). The amplitude and frequency plot clearly show the higher amplitude energies associated with mesoscale pressure variations at frequencies of less than 0.5 cpd. However, very clear and separate peaks also occur at 1 and 2 cpd (In following figures the spectrum is truncated at 3.5 cpd and amplified for clarity).

224 The peaks at 1 cpd (denoted S_1) and 2 cpd (denoted S_2) in atmospheric pressure data 225 were recognised shortly after the invention of the barometer by Torricelli in 1643 226 (Ananthakrishnan et al, 1984). There has been much debate about their origin. They are 227 not gravitational tides as they do not vary with lunar time (Thomson (Lord Kelvin), 1882). 228 It is considered that they are associated with thermal energy caused by heating the upper 229 atmosphere as the earth rotates (Palumbo, 1998). The primary generating signal is 230 approximately a square wave, corresponding to the sun rising and then setting 12 hours 231 later as the earth rotates. The amplitude and phase of this S_1 wave were extracted from 232 the signal (Fig. 4) using a FFT based band-pass filter with a cut off at 1.0 cpd and a band 233 width of 0.05 cpd. The maximum occurs at 12:00 and the minimum at 00:00. However, 234 the amplitude of this wave varies considerably throughout the seasons (Acworth and 235 Brain, 2008). By contrast, the 2 cpd wave (FFT band-pass filter with cut off at 2.0 cpd and 236 a bandwidth of 0.05 cpd) has maxima at 04:00 and 16:00 with corresponding minima at 237 10:00 and 22:00 and has almost constant amplitude with time.

238 Thermo-tidal theory (Chapman and Lindzen, 1970) is used to explain the tides with solar 239 heating and the inclusion of energy dissipation in the atmosphere due to ozone and water 240 vapour excitation being the main casual agents. In general, the S_2 is predicted by this 241 theory to have larger amplitude and is much more regular than S₁. This is explained by 242 the S_1 tide being produced by a regionally varying number of interfering wave 243 components that are mutually destructive. It is seen that the theory accounts for most of 244 the observations but can still not account for the fact that the observed maximum in S_1 245 occurs at 10:00 local time instead of the theoretically predicted 09:00 local time.

246 There are various processes that can influence the observed water level signal in a well 247 at 1 cpd or 2 cpd. For this reason, we will refer here to the S_1 and S_2 atmospheric tides as 248 S_{1a} and S_{2a} in the analysis that follows. Irrespective of the processes responsible for the 249 formation of S_{1a} and S_{2a} we can still use this very regular excitation of the ground and the 250 response of the groundwater level, to determine barometric efficiency (Jacob, 1940). The 251 regularity of the S_{1a} and S_{2a} components is a significant advantage over using the much 252 more variable mesoscale response at frequencies below 0.5cpd and we will return to this 253 later.

254 **3.2. Surface Water Levels at Elfin Crossing Stream Gauge**

Figure 5 There is a permanent deep pool between the line of the bores and the surface water transducer installation. Since a vented gauge transducer was used at this site, there is no evidence of any atmospheric pressure signal in the record (Figure 5).

259 There is a small amplitude signal at 1 cpd in the amplitude and frequency plot of the 260 creek data (Figure 5). This is can be resolved using a FFT band-pass filter (cut off at 2.0 261 cpd with a bandwidth of 0.02 cpd) to be a frequency with a maximum at 08:00 in the 262 morning and a minimum at 20:00 in the evening. This should not be confused with a 263 barometric pressure response (S_{1a}) that has a maximum at 12:00 and a minimum at 264 00:00. The amplitude of the water level response is also much smaller than the S_{1a} of the 265 atmospheric data (Fig 5). Note also the lack of resolution in the output from the 266 transducer deployed at the site as the time series data for the hydraulic head shows step 267 changes.

268 **3.3. Borehole Records**

The data from BH 7.1 (Fig. 6), EC 17 (Fig. 7) on the opposite bank under the trees, and BH 12.2 (Fig. 8) on the north-west bank of the area are presented. These loggers were each of the absolute pressure type (Details in Table 2). To facilitate comparison, each of the 3 figures shows DFT pairs of three components: the atmospheric pressure at BH 8; the uncorrected output for the data logger showing the total pressure head (atmospheric

- and water); and the hydraulic head (total pressure head with the atmospheric component
- 275 removed by subtraction and referenced to Australian Height Datum (AHD)).
- 276 **3.3.1.Borehole 7.1**

277 Figure 6

278 Borehole 7 contains piezometers at 248 m AHD (BH 7.1) and 242 m AHD (BH 7.2) 279 installed in a mixture of sands and gravels that are hydraulically connected to the Creek, 280 as seen from their response to floods. The middle plot in Fig. 6 shows the total pressure 281 head (water plus atmosphere) recorded by the absolute gauge pressure transducer. It is 282 clear that the total pressure head is strongly influenced by the atmospheric pressure (top 283 panel in Fig. 6) and in phase with the atmospheric pressure. The strong 1 and 2 cpd 284 spectra (S_{1a} and S_{2a} components) are clearly seen in the amplitude and frequency plot 285 shown to the right of the time series data. Note that the time series data is only a subset 286 of the complete record, selected to best represent the variability in the data set and at the 287 same time visualise the variability at the important frequencies. The Fourier analysis to 288 derive the amplitude and frequency plot was carried out on the complete record of data, 289 but in the plot, the record is shown only to 3.5 cpd as there is no significant energy 290 contained in the frequency spectrum between 3 cpd and the Nyquist frequency (48 cpd).

The lower plot in Fig 6 shows the hydraulic head record with the atmospheric signal removed (by subtraction). The strong variability noted in the middle plot (time series) is completely removed while the amplitude frequency plot shows a simple distribution with a slight frequency component at 1 cpd, but no energy at 2 cpd. The S_{1a} and S_{2a} signals have been eliminated.

In theory the water pressure at the water table represents atmospheric pressure (Domenico and Schwartz, 1998; Ingebritsen et al, 2006). Accepting this definition, removal of the atmospheric component from the total pressure head in a perfectly unconfined aquifer should leave only the elevation head of the water table. An aquifer should be considered perfectly unconfined if air can move down through the formation instantaneously in response to changes in atmospheric pressure. Norum and Luthin 302 (1988) investigated the conditions generated by an advancing wetting front and 303 demonstrated that confined conditions could be generated for a time if the air in the 304 unsaturated zone was unable to escape.

305 As the thickness of the unconfined zone increases; resistance to air flow, the hydraulic 306 conductivity of the material and the radius of the well can all influence the well response 307 (Rojstaczer and Riley, 1990) producing the possibility that unconfined aquifers can show 308 a response to atmospheric pressure change, albeit with a significant phase lag and 309 diminished amplitude. However, the shallow well depths in this study (<30 m), the small 310 diameter of the piezometers (50 mm) and the relatively high hydraulic conductivity of the 311 sands and gravels all make this unlikely. The absence of any response to atmospheric 312 pressure in the data presented (Fig 6) confirm this analysis.

Examination of the phase of the remaining 1 cpd energy using TSoft shows a maximum at 05:00 and a minimum at 17:00 and is not to be confused with the atmospheric energy at the same frequency (S_{1a}) of much greater amplitude and a different phase.

316 **3.3.2.Piezometer EC 17**

317 In contrast to the data from BH 7.1, EC 17 is located in trees on the opposite bank of the 318 creek. The screened depth is approximately 6 m below ground surface with the elevation 319 of the screen set at 4 m below the water table. The corrected hydraulic head response of 320 this piezometer (Fig. 7) is similar to that of BH 7.1 (Fig 6) and the creek (Fig 5), 321 confirming that this piezometer is in an unconfined portion of the aquifer system. As with 322 the other two water table responses, there is a strong observed signal at 1 cpd that has a 323 maximum at 06:00 and a minimum at 18:00. There is an interesting phase lag of the 1 324 cpd signal between BH 7.1 at 248 m AHD and EC17 at 250m AHD, of approximately 1 325 hour that requires further investigation.

326 Figure 7

327 **3.3.3.Borehole 12.2**

BH 12 was completed close to BH 7 (Figs 1 and 2) to provide a vertical profile of piezometers on the west side of the creek. BH 12.2 was completed at approximately 229 m AHD and lies beneath a confining layer of clay. It is not clear from the available drilling data how laterally extensive this clay layer is. The hydraulic head at BH 12.2 is approximately 1.25 m below that at BH 7.1, indicating a significant downward gradient.

333 The total pressure head is dominated by the atmospheric pressure (Fig. 8), similar to BH 334 7.1 and EC 17. There is also a small response at a frequency of approximately 1.9 cpd 335 visible in the total head data (middle plot in Fig. 8). Importantly, subtraction of the 336 atmospheric pressure leaves a residual impact where the response is now inverted (lower 337 plot in Fig. 8) and as predicted for confined aquifers by Jacob (1940). This is clearly seen 338 in the time series data (Fig. 9) where a reduction in atmospheric pressure is matched by 339 an increase in hydraulic head. BH 7.1 is included in Fig.9 to demonstrate the difference in 340 response between the unconfined BH 7.1 and BH 12.2.

Examination of the DFT pair for the corrected data (Fig. 8 lower plot) shows five small peaks that have the same frequencies as the earth tides (Bredehoeft, 1967) shown in Table 2 (Wahr, 1995; Merritt, 2004). Note also that the small response in the total pressure plot (middle plot in Fig. 8) is now recognised as the M_2 lunar frequency at 1.93 cpd.



354 corresponding to the solar solstices at mid-June and mid-December with a minimum in 355 mid-September at the equinox. This response is believed to be the result of superposition 356 of both earth tides (K_1) and atmospheric tides (S_{1a}), noting again that S_{1a} is expected to 357 vary seasonally. The 1.93 cpd component shows very constant amplitude throughout the 358 record and is seasonally independent. This component is the main lunar semi-diurnal 359 (M_2) signal emanating solely from the Earth tide response. The 2.0 cpd component shows 360 some seasonality but less than the 1.0 cpd component and is not clearly associated with 361 the seasons. The observed signal is believed to be the result of superposition of the S_{2a} 362 (atmospheric tide) and S_2 (earth tide) components. The variations seen at the beginning 363 and end of each record may be attributed to edge effects caused by the band-pass filter.

Figure 10

The various amplitude changes (Fig. 10) for the different frequency components of the hydraulic head in BH 12.2 reveal a complex situation. The observed 1.0 cpd and the observed 2.0 cpd signals in the BH 12.2 spectrum are the result of several processes. Atmospheric pressure and earth tides are both incorporated. However, the 1.93 (M₂) signal appears to only be caused by the Earth tide at this frequency. The amplitude and suggested causes of the various tide components identified by the DFT in the data are given in Table 3, with data for BH 7.1 and EC 17 included for comparison.

372 **Table 3**

373 4. DISCUSSION

4.1. Optimising the sampling frequency of water levels

Inspection of the atmospheric data in Fig. 4, or any of the DFT pairs (Figs 5 to 8) indicates that there is no significant information at a frequency of greater than 3 cpd. Using the Nyquist frequency, it is clear that sampling at 6 cpd will satisfactorily resolve a periodic signal at 3 cpd. Following this logic, sampling every 4 hours (6 cpd) will recover all the components of the groundwater signal. Sampling at greater than 6 cpd could therefore be considered as oversampling and wasteful of system resources. However, we acknowledge that the timing of non-sinusoidal events like the arrival of a flood peak could

- 382 require a higher sampling frequency depending on the desired resolution of the shape of
- the flood hydrograph.

384 **4.2.** Evapotranspiration and its spectral signature

A significant 1.0 cpd signal exists in piezometers installed in the unsaturated zone (Maules Creek surface water level shown in Fig. 5, BH 7.1 in Fig 6 and EC 17 shown in Fig. 7). This is not an earth tide response as the other earth tide components are absent and is also not a residual of an atmospheric pressure response as there is no S_{2a} component. The probable explanation for this response is photosynthetic demand by phreatophytes (groundwater extracting plants) on the aquifer system during daylight hours (e.g. White, 1932; Loheide et al., 2005).

392 To prove this hypothesis, solar radiation is plotted together with water levels for the BH 9 393 (Fig. 2) record in Fig. 11. Although the solar radiation data is from a site 11 km distant, 394 there will not be significant variation from the Elfin Crossing site. Daily short-wave 395 radiation totals (MJm⁻²), potential evaporation and rainfall (mm) are also shown in Fig. 11. 396 The concordance between solar radiation and potential evaporation is entirely expected. 397 The observation that water levels fall as soon as the solar radiation begins at the start of 398 the day and continues until the sun sets, after which water levels begin to recover 399 complies with the literature (e.g. Butler et al., 2007; Gribovszki et al., 2010). These data 400 show that the roots of the phreatophytes growing around the site, large river red gums, 401 reach into the gravel aquifer at Elfin Crossing and act like cyclic groundwater pumps.

The period between 6th and 8th November was cloudy and there was little incoming shortwave radiation received. The lack of photosynthesis by the trees over this period is clearly shown by the absence of the daily drawdown in the groundwater level indicating that the 'groundwater pumps' had been closed down over this period.

406	Figure 11
407	Further detail on the photosynthetic activity can be provided by analysing the 1.0 cpd
408	signal after isolating it using a FFT band-pass filter. The time series of 1.0 cpd signals for

409 EC17, BH 7.1 and the creek are shown in Fig. 12.

Figure 12
The amplitude of the EC 17 site is considerably larger than that at BH 7.1 closer to the
creek. There is also a phase lag (not shown) of between 15 min and 1 hr, with BH 7.1
leading EC 17. A very clear increase in amplitude in EC 17 and BH 7.1 is also seen as
the solar radiation input increases between winter and summer.
The decrease of the fluctuation in amplitude towards the creek may be attributed to the
increasing supply of surface water (Butler et al., 2007; Johnson et al., 2013) in
combination with the spatial distribution of the phreatophytes (with less trees near BH
7.1). It is also interesting to note that the amplitude of the 1.0 cpd signal for the creek
does not show the same degree of seasonality as that for EC 17 and BH 7.1.
Water level fluctuations induced by phreatophytes have extensively been exploited for the
quantification of evapotranspiration (e.g. White, 1932; Loheide et al., 2005; Gribovszki et
al., 2010) including the estimation of surface water and groundwater fractions consumed
(Johnson et al., 2013). However, the spectral signature of these fluctuations and its
usefulness for the determination of surface water groundwater connectivity has not yet
been reported. Fig. 12 illustrates clearly the usefulness of the Fourier analysis approach.
4.3. Earth tide signals and the confined aquifer response
At the unconfined BH 7.1, air is able to move through the unsaturated zone above the
water table so that the water table represents atmospheric pressure. Subtracting the
atmospheric pressure signal from the total pressure, recorded by the absolute gauge
transducer, completely removes the atmospheric components recorded in the total
pressure record. This is clearly shown in Figs. 6 and 7 and is not surprising given the
shallow depth to the water table (approx. depth 1 – 2 m), the small diameter of the
piezometer tube (30 mm) and the relatively coarse grained nature of the sediments at
Maules Creek. Each of these factors will act to supress the possibility of atmospheric
tides in the unconfined aquifer (Rojstaczer and Riley, 1990).

However, when the atmospheric pressure is deducted from the total pressure signal forBH 12.2, a different result occurs in that the response to atmospheric pressure is not

438 removed but (partially) inverted. This is shown in Figs. 8 and 9 and can be 439 conceptualised as the result of removing too much of the pressure signal from the record 440 thus causing the inversion. More erudite explanations are provided by Jacob (1940), van 441 de Kamp & Gale (1983), Merritt (2004), Ingebritsen et al (2006) and Price (2009): The 442 reason for the over-correction is that only a part of the atmospheric loading is initially 443 transferred to the water column in a confined aquifer with the balance of the load 444 supported by the aquifer skeleton. Subtracting all the atmospheric pressure therefore 445 provides too much of a correction. It is noted that a vented transducer will produce the 446 equivalent result with the same partial inversion of the atmospheric signal.

447 The amplitude and phase of the atmospheric pressure record at 1.0 cpd and 2.0 cpd and 448 the hydraulic head data for the BH 12.2 record are shown in more detail in Fig.13. The 449 amplitudes for these data have been kept the same in these plots so that the comparative 450 size can be appreciated. There is significant seasonal variation shown in both the 1.0 cpd 451 atmospheric data, and to a lesser extent in the 1.0 cpd data for BH 12.2 (Fig 13 a). 452 Interestingly, there is a significant phase difference between the two data sets (Fig. 13 b) 453 of approximately 5 hours. This is instead of the 12 hours that would be expected if the 454 atmospheric tide loading was expressed in the hydraulic head record as a simple 455 inversion. We take this to indicate that there is interference from an Earth tide component 456 (K_1) at the same frequency as the atmospheric pressure component (S_{1a}) , but of a 457 different phase.

458 **Figure 13**

The 2.0 cpd signals for the atmospheric pressure and for the BH12.2 record show no seasonal variation (Fig 13 c). Furthermore, the phase lag between the individual components is closer (5.5 hours) to the expected 6 hours (Fig 13 d).

462 **4.4. Estimate of barometric efficiency from the ratio of the S₂ and M₂ amplitudes**

463 Jacob (1940) demonstrated that the barometric efficiency of an aquifer could be 464 calculated from the ratio of the aquifer response to the atmospheric pressure change 465 driving that response. It has been demonstrated above that the very clear atmospheric signal at 1 and 2 cpd produces an equally clear response in the hydraulic head data at the same frequencies. However, the 1 cpd data is significantly impacted by seasonal variation and other factors so that it would be beneficial to use the 2 cpd signal for this calculation. We have also noted that the 2 cpd signal in the hydraulic head comprises the input from both the atmospheric tide (S_{2a}) and the Earth S_2 tide. It is useful to define this (hydraulic head) response as S_{2h} , where

472
$$S_{2h} = S_{2h-s} + S_{2h-rorth}$$
. Equation 4

473 We can also define a hydraulic head response to the M_2 earth tide as M_{2h} . The barometric 474 efficiency can be calculated from the ratio of S_{2a} and S_{2h-a} .

To derive a value for S_{2h-a} , we need to find a value for $S_{2h-earth}$. Fortunately, we can use the theoretically calculated Earth tides with the measured value of M_{2h} to provide this value. The Tsoft package (Tsoft, 2013) can be used to calculate the theoretical value of the earth tides for a given latitude and time. The ratio of the amplitude of the M_2 and S_2 components of the Earth tide will be constant. We can use this ratio along with the value of M_{2h} to derive $S_{2h-earth}$.

In Fig. 14, the earth tides at 1.93 and 2.00 cpd (M_2 and S_2) are shown for Maules Creek (tide shown in red scaled on the left hand axis). The observed data for BH 12.2 over this frequency spectrum is also shown in Fig. 14 (tide shown in blue and scaled on the righthand axis).

485 **Figure 14**

486 At Maules Creek, the ratio of the $S_2:M_2$ Earth tides is 0.488 (shown in Fig. 14). The M_{2h} 487 (1.93 cpd) signal in the observed response can be multiplied by the ratio (0.488) to derive 488 the earth tide component $S_{2h-earth}$. Subtraction of $S_{2h-earth}$ from S_{2h} allows recovery of the 489 atmospheric component of the observed data (S_{2h-a} in Fig. 14) previously hidden in S_{2h} .

490 S_{2h-a} can then be used to calculate the barometric efficiency (BE) of the aquifer (Jacob,
491 1940; van de Kamp & Gale, 1983)

492
$$BE = \frac{dh}{dp} = \frac{S_{2h-a}}{S_{2a}} = \frac{0.000564}{0.00015} = 0.069.$$
 Equation 5

The components in Equation 5 are given in terms of metres head, as the atmospheric pressure is recorded as a head (Table 3) rather than a pressure, by the logger software. The calculated value of BE is low (a rigid aquifer would have a BE of 1.0) and suggests that the aquifer material is not rigid but deformable. This is entirely consistent with our knowledge of the geology from the drilling records.

- 498 If we assume that undrained conditions apply at the frequencies involved (Rojstaczer,
 499 1988) and recognise that (Jacob, 1940, van de Kamp and Gale, 1983)
- 500 $BE = 1 \gamma$, Equation 6

501 where γ is the loading efficiency. Parameter γ can be expressed as a ratio of terms

- 502 involving compressibility
- 503 $\gamma = \frac{\alpha}{\mathfrak{O}\beta + \alpha}$, Equation 7

where α is the material compressibility and β (= 4.4 x 10⁻¹⁰ Pa⁻¹) is the fluid compressibility (at a temperature of 20°C), and α is the porosity. Equation 7 can be rearranged to provide solutions for α given an appropriate value for the porosity. For example α = 1.187 x 10⁻⁹ Pa⁻¹ for a typical porosity of 0.2. Values of compressibility for undrained and unconsolidated media are not often measured as they are not of interest to the geotechnical industry however Berryman (2010) provides some values for undrained and unconsolidated sands that are of the same order.

511 With α , β and θ either known or assumed, the value of specific storage for the formation

512 $S_s = \rho g (\alpha + \theta \beta)$ Equation 8

can also be calculated. This approach gives a value of 1.25×10^{-5} for the specific storage ($\theta = 0.2$). The use of the barometric efficiency to generate a value of specific storage is

515 of great use in regional groundwater analysis (Harrington and Cook, 2011, and many 516 others).

517 **5. CONCLUSIONS**

This paper illustrates how Fourier analysis of water level data using the Discrete Fourier Transform (DFT) provides a useful tool to examine water level data in the frequency domain. Significant frequencies in the data can be easily resolved, in contrast to the great difficulty in resolving these separate high frequency signatures in the time domain. More importantly, the amplitude and phase of these frequencies can be isolated and then plotted back in the time domain so that their relationship to physical processes can be better explored.

In this paper we have made use of data sets collected with both vented and non-vented (absolute gauge) transducers. Inspection of this data in the frequency domain reveals the presence of significant tides at a frequency equal to, or greater than, one cycle per day. These are generated by a mixture of thermally derived atmospheric tides, earth tides and changes caused by variation in evapotranspirative fluxes. The data for a variety of unconfined and confined head data is analysed.

531 Unconfined aquifer data shows that the thermally induced atmospheric tides are not 532 retarded in their progression through the unsaturated zone and they are completely 533 removed by subtraction of the atmospheric pressure from the total pressure measured by 534 absolute gauge transducers installed at the site.

The recognition of the characteristic Earth tide frequencies $(O_1, K_1, M_2, S_2 \text{ and } N_2)$ in the frequency spectrum for a deeper piezometer at the site indicates that the aquifer is confined at this location. Under confined conditions, the response at the piezometer is formed by a mixture of thermal atmospheric tides and earth tide components. A method of separating these components is described and the barometric efficiency is determined.

540 Fourier analysis also helps to determine the best sampling frequency for long-term 541 groundwater monitoring by considering the necessary resolution in both time and 542 frequency domain. The analysis demonstrates that a sampling interval of 4 hours (6 cpd)

543 is sufficient to capture the essential system characteristics illustrated in this study. It is 544 recommended that data logging for long-term groundwater monitoring move towards the 545 less frequent measurement unless there are other grounds for maintaining more frequent 546 measurements.

547

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561 References

Acworth RI, Brain T (2008) Calculation of barometric efficiency in shallow piezometers using water levels, atmospheric and earth tide data. Hydrogeol J 16:1469-1481. DOI 10.1007/s10040-008-0333-y

Ananthakrishnan R, Maliekal JA and Aralikatti SS (1984) Atmospheric tidal oscillations
Part 1. Historical Development. Current Science 53.18:945-951.

567 Andersen MS, Acworth RI (2009) Stream-aquifer interactions in the Maules Creek 568 catchment, Namoi Valley, New South Wales, Australia. Hydrogeol J 17:2005-2021

- 569 Berryman JG (2010) Inverse problem in anisotropic poroelasticity: Drained constants from
- 570 undrained ultrasound measurements. Lawrence Berkeley National Laboratory
- 571 http://escholarship.org/uc/item/5nb876j3.
- 572 Bredehoeft JD (1967) Response of well-aquifer systems to earth tides. J Geophys Res 573 72:3.075 – 3.087
- 574 Butler JJ, Kluitenberg GJ, Whittemore DO, Loheide SP, Jin W, Billinger MA, Zhan X
- 575 (2007) A field investigation of phreatophyte-induced fluctuations in the water table. Wat
- 576 Resour Res 43:W02404, doi:10.1029/2005WR004627.
- 577 Chapman S, Lindzen RS (1970) Atmospheric Tides Thermal and Gravitational. Reidel,
- 578 Dordrecht-Holland.
- 579 Davis JC (1986) Statistics and data analysis in Geology Second Edition. John Wiley & 580 Sons Inc., New York.
- 581 Doodson AT (1921) The harmonic development of the tide-generating potential. Proc Roy
 582 Soc London A100:305-329.
- 583 Domenico PA, Schwartz FW (1998) Physical and Chemical Hydrogeology, 2nd Ed, Wiley.

584 Emery WJ, Thomson RE (2004) Data analysis methods in physical oceanography (2nd
585 Edition). Elsevier.

- 586 Fourier JBJ (1822) Analytical theory of heat, Didot.
- 587 Gribovszki Z, Szilágyi J, Kalicz P (2010) Diurnal fluctuations in shallow groundwater
- 588 levels and streamflow rates and their interpretation A review. J Hydrol 385:371-383.
- 589 Harrington G, Cook P (2011) Mechanical loading and unloading of confined aquifers:
- 590 implications for the assessment of long-term trends in potentiometric levels. Waterlines
- 591 Report Series No 51, National Water Commission, Australian Government.
- 592 Hseih PA, Bredehoeft JD, Farr JM (1987) Determination of Aquifer Transmissivity from
- 593 Earth Tide Analysis. Water Resour Res 23.10:1824-1832.

594 Ingebritsen S, Sanford W, Neuzil C (2006) Groundwater in Geologic Processes 2nd Ed,

595 Cambridge University Press.

- 596 Jacob CE (1940) On the flow of water in an elastic artesian aquifer. American 597 Geophysical Union Transactions, Part 2, p 574-586.
- Johnson B, Malama B, Barrash W, Flores AN (2013) Recognizing and modeling variable drawdown due to evapotranspiration in a semiarid riparian zone considering local differences in vegetation and distance from a river source. Wat Resour Res 49:030-1039. doi:10.1002/wrcr.20122.
- Loheide SP, Butler JJ, Gorelick SM (2005) Estimation of groundwater consumption by
 phreatophytes using diurnal water table fluctuations: A saturated-unsaturated flow
 assessment. Water Resour Res 41:W07030. doi:10.1029/2005WR003942.
- 605 McCallum AM, Andersen MS, Giambastiani BMS, Kelly BFJ, Acworth RI (2013) River-606 aquifer interactions in a semi-arid environement stressed by groundwater abstraction.
- 607 Hydrol Proc 27:1072-1085.
- 608 Merritt LM (2004) Estimating Hydraulic Properties of the Floridan Aquifer System by
- 609 Analysis of Earth-Tide, Ocean-Tide, and Barometric Effects, Collier and Hendry Counties,
- 610 Florida. USGS Water-Resources Investigations Report 03-4267.
- New South Wales Department of Primary Industries, Office of Water website.
 http://waterinfo.nsw.gov.au/ (Accessed 15 January, 2014).
- 613 Norum DI, Nuthin JN (1968) The effects of entrapped air and barometric fluctuations on
- the drainage of porous mediums. Water Resour Res 4.2:417-424.
- 615 Oppenheim AV, Schafer RW, Buck JR (1999) Discrete-time signal processing. Prentice
- 616 Hall, Upper Saddle River.
- 617 Palumbo A (1998) Atmospheric tides. J Atmos Sol-Terr Phys 60:279-287

618 Post VEA, von Asmuth JR (2013) Review: Hydraulic head measurements-new
619 technologies, classic pitfalls. Hydrogeol J 21: 737-750.

620 Price M (2009) Barometric water-level fluctuations and their measurement using vented
621 and non-vented pressure transducers. Q J Eng Geology Hydrogeol 42: 245-250.
622 doi:10.1144/1470-9236/08-084.

623 Rau GC, Andersen MS, McCallum AM, Acworth RI (2010) Analytical methods that use

624 natural heat as a tracer to quantify surface water-groundwater exchange, evaluated using

625 field temperature records. Hydrogeol J 18:1093-1110.

- 626 Rojstaczer S (1988a) Determination of Fluid Flow Properties From the Response of
- 627 Water Levels in Wells to Atmospheric Loading. Water Resour Res 24.11:1927-1938.

Rojstaczer S (1988b) Intermediate period response of water levels in wells to crustal
strain: sensitivity and noise level. J Geophys Res 93.B11:619-634.

- 630 Rojstaczer S, Agnew DC (1989) The Influence of Formation Properties on the Response
- 631 of Water Levels in Wells to Earth Tides and Atmospheric Loading. J Geophys Res
- 632 14.B9:403-412.

633 Smith JO (2007) Mathematics of the Discrete Fourier Transform (DFT) with Audio 634 Applications. 2nd ed., Online Book, http://ccrma.stanford.edu/~jos/mdft/.

- 635 Sorensen JPR, Butcher AS (2011) Water Level Monitoring Pressure Transducers-A
- 636 Need for Industry-Wide Standards. Groundwater Monitoring & Remediation, 31: 56–62.
- 637 doi: 10.1111/j.1745-6592.2011.01346.x
- 638 Thomson TW (Lord Kelvin) (1882) On the thermodynamic acceleration of the Earth's

639 rotation. Proc R Soc Edinburgh Session 1881-82 11:396-404

- 640 TSoft (2013), A software package for the analysis of Time Series and Earth Tides,
- 641 <u>http://seismologie.oma.be/TSOFT/tsoft.html (Accessed 15 Jan, 2014)</u>

Van de Kamp G, Gale JE (1983) Theory of earth tides and barometric effects in porous

643 formations with compressible grains. Water Resour Res 19:538-544.

- 644 Volland H (1996) Atmosphere and earth's rotation. Surv Geophys 17.1:101-144
- 645 Wahr J (1995) "Earth Tides", Global Earth Physics, A handbook of physical constants.
- 646 AGU Reference Shelf 1, pp 40-46.
- 647 Weeks EP (1979) Barometric Fluctuations in Wells Tapping Deep Unconfined Aquifers.
- 648 Water Resour Res 15.5:1167-1176.
- 649 White WN (1932) A method of estimating ground-water supplies based on discharge by
- rom s. 650 plants and evaporation from soil: Results of investigations in Escalante Valley, Utah.
- 651 Water Supply Paper 659-A, US Geological Survey.
- 652

654 List of Figures

- 1. Location of the Maules Creek Catchment in New South Wales, Australia.
- 656 2. Cross section for Elfin Crossing boreholes.
- 3. Illustration of the Discrete Fourier Transform (DFT) using simple sine waves: a) 1
 cycle per day (cpd) and b) the DFT of a; c) 2 cpd and, d) the DFD of c; e) 0.2 cpd,and
 f) the DFD of e; f) the summation of these three components (1 cpd, 2 cpd and 0.2
 cpd), and h) the resulting DFD.
- 4. The atmospheric record for the Barologger in BH 8 showing the DFT pairs: a)
 pressure and temperature, and b) the DFT of the atmospheric pressure. The
 temperature record from the barlogger (red line) is included in part a) to demonstrate
 that there is no temperature dependence on the pressure record.
- 5. DFT pairs for atmospheric pressure observed at BH 8 and the Elfin Crossing surface
 water level gauge. The complete spectrum is shown in the frequency amplitude plot.
 a) Time series of barometric pressure; b) DFT of a; c) time series of Elfin Crossing,
 and d) DFT of c.
- 6. DFT pairs for piezometer BH 7.1, installed at 10 m depth on the north-west bank of
 Elfin Crossing (see Fig. 2 for location); a) Time series of barometric pressure and b)
 is the DFT of a; c) time series of BH 7.1 total pressure and d) is the DFT of c; e) the
 time series of BH7.1 water levels and f) is the DFT of e.
- 673 7. DFT pairs for piezometer EC 17, installed at 5.5 m depth on the opposite bank
 674 beneath tree cover (see Fig. 2 for location); a) Time series of barometric pressure
 675 and b) is the DFT of a; c) time series of EC 17 total pressure and d) is the DFT of c;
 676 e) the time series of EC 17 water levels and f) is the DFT of e.
- 677 8. DFT pairs for BH 12.2, installed at 30 m depth close to piezometer 7.1 (see Fig. 2 for
 678 location); a) Time series of barometric pressure and b) is the DFT of a; c) time series
 679 of BH 12.2 total pressure and d) is the DFT of c; e) the time series of BH 12.2 water
 680 levels and f) is the DFT of e. The Earth tide frequencies are identified in the DFT plot.

- 681 9. Comparison of a) corrected hydraulic heads and b) atmospheric pressure, for BH 7.1
- and BH 12.2. Note the inverted phase of the atmospheric pressure signal in BH 12.2
- 683 data and also the completely different phase and frequencies of the unconfined signal
- 684 of BH 7.1.
- 685 10. Envelopes of the seasonal variation of the K₁, M₂ and S₂ components of the hydraulic
 686 head at BH 12.2.
- 687 **11.** Composite data for BH 9 at installed at 12.7 m depth (close to EC 17) showing water
 688 level change, solar radiation and potential evaporation.
- 689 **12.** Plots showing the amplitude vs time of the 1 cpd signal in EC17, BH 7.1 and the 690 creek.
- 69113. Time series data for the 1 cpd and 2 cpd components of the atmospheric pressure692and the BH 12.2 hydraulic head data: a) data for the total series for S_1 and K_1 693frequencies showing atmosphere in magenta and BH 12.2 in green; b) expanded to694show the phase and amplitude relationships; c) data for the S_2 frequencies; d)695expanded to show the phase and amplitude relationships.
- 696 14. Barometric efficiency calculation: The spectrum of the calculated earth tide is shown
 697 in red and scaled on the left-hand axis. The measured spectrum of the BH 12.2
 698 response is shown in blue and scaled on the right-hand axis.
- 699

700 15.

701 Table 1. Construction and logger details for the piezometers used in this study (locations

are shown in Fig. 2). All unvented loggers were manufactured by Solinst for a range of 20

703 m (1.5 m for the baro logger).

Name	Elevation to top of casing (m AHD)	Screen length (m)	Elevation of mid- point of screen (m AHD)	Logger ID
BH 7.1	258.721	0.15	248.026	2004775 Edge
BH 7.2	258.721	1.5	242.241	1058991 Gold
BH 8 (baro logger)	258.382	1.5	253.587	1044805 Gold
BH 9	254.275	1.0	241.640	1044960 Gold
BH 12.2	259.164	0.15	229.389	2003344 Edge
EC17	255.67	0.15	250.180	1057878 Gold

704

705 Table 2. Principal solar and lunar earth tide components.

Symbol	Frequency (cpd)	Period (hours)	Vertical amplitude	Explanation
			(mm)	
O ₁	0.92953	25.819	158.11	Main lunar diurnal
K ₁	1.00273	23.934	191.78	Lunar-solar diurnal
M ₂	1.93227	12.421	384.83	Main lunar semi-diurnal
S ₂	2.00000	12.000	179.05	Main solar semidiurnal
N ₂	1.89598	12.658	73.69	Lunar elliptic (lunar semi-diurnal)

708

- Table 3. Amplitude and probable cause of the observed spectra at 1.00, 1.93 and 2.00
- 710 cpd frequencies.

Location	Tide component	Amplitude	Probable Cause
	(cpd)	(mm)	
Bore 8 (baro logger)	1.0	7.10	S _{1a}
	2.0	8.15	S _{2a}
BH 7.1	1.0	0.57	Evapotranspiration
BH 12.2	0.93	0.55	Earth tide O ₁
	1.0	0.68	S_{1a} mixed with earth tide K_1
	1.90	0.26	Earth tide N ₂
	1.93	1.16	Earth tide M ₂
	2.0	1.13	$S_{2a}\xspace$ mixed with earth tide S_2
EC17	1.0	1.15	Evapotranspiration
	2.0	0.3	Evapotranspiration
Stream	1.0	0.55	Evapotranspiration
		0	2



1. Location of the Maules Creek Catchment in New South Wales, Australia. 204x261mm (300 \times 300 DPI)





3. Illustration of the Discrete Fourier Transform (DFT) using simple sine waves: a) 1 cycle per day (cpd) and b) the DFT of a; c) 2 cpd and, d) the DFD of c; e) 0.2 cpd,and f) the DFD of e; f) the summation of these three components (1 cpd, 2 cpd and 0.2 cpd), and h) the resulting DFD. 149x111mm (300 x 300 DPI)



4. The atmospheric record for the Barologger in BH 8 showing the DFT pairs: a) pressure and temperature, and b) the DFT of the atmospheric pressure. The temperature record from the barlogger (red line) is included in part a) to demonstrate that there is no temperature dependence on the pressure record. 165x102mm (300 x 300 DPI)



5. DFT pairs for atmospheric pressure observed at BH 8 and the Elfin Crossing surface water level gauge. The complete spectrum is shown in the frequency amplitude plot. a) Time series of barometric pressure; b) DFT of a; c) time series of Elfin Crossing, and d) DFT of c. 130x64mm (300 × 300 DPI)

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6. DFT pairs for piezometer BH 7.1, installed at 10 m depth on the north-west bank of Elfin Crossing (see Fig. 2 for location); a) Time series of barometric pressure and b) is the DFT of a; c) time series of BH 7.1 total pressure and d) is the DFT of c; e) the time series of BH7.1 water levels and f) is the DFT of e. 188x132mm (300 x 300 DPI)





7. DFT pairs for piezometer EC 17, installed at 5.5 m depth on the opposite bank beneath tree cover (see Fig. 2 for location); a) Time series of barometric pressure and b) is the DFT of a; c) time series of EC 17 total pressure and d) is the DFT of c; e) the time series of EC 17 water levels and f) is the DFT of e. 188x130mm (300 x 300 DPI)



8. DFT pairs for BH 12.2, installed at 30 m depth close to piezometer 7.1 (see Fig. 2 for location); a) Time series of barometric pressure and b) is the DFT of a; c) time series of BH 12.2 total pressure and d) is the DFT of c; e) the time series of BH 12.2 water levels and f) is the DFT of e. The Earth tide frequencies are identified in the DFT plot.

187x129mm (300 x 300 DPI)



9. Comparison of atmospheric pressure and corrected hydraulic heads for BH 7.1 and BH 12.2. Note the inverted phase of the atmospheric pressure signal in BH 12.2 data and also the completely different phase and frequencies of the unconfined signal of BH 7.1. 180x119mm (300 x 300 DPI)



10. Envelopes of the seasonal variation of the K1, M2 and S2 components of the hydraulic head at BH 12.2. 243x331mm (300 x 300 DPI)



11. Composite data for BH 9 at installed at 12.7 m depth (close to EC 17) showing water level change, solar radiation and potential evaporation. 175x111mm (300 x 300 DPI)

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12. Plots showing the amplitude vs time of the 1 cpd signal in EC17, BH 7.1 and the creek. 184x127mm (300 x 300 DPI)



13. Time series data for the 1 cpd and 2 cpd components of the atmospheric pressure and the BH 12.2 hydraulic head data: a) data for the total series for S1 and K1 frequencies showing atmosphere in magenta and BH 12.2 in green; b) expanded to show the phase and amplitude relationships; c) data for the S2 frequencies; d) expanded to show the phase and amplitude relationships. 266x369mm (300 x 300 DPI)



14. Barometric efficiency calculation: The spectrum of the calculated earth tide is shown in red and scaled on the left-hand axis. The measured spectrum of the BH 12.2 response is shown in blue and scaled on the right-hand axis. 170x154mm (300 x 300 DPI)