Piezometric tides are universal. How and to what extent can they be used as a low-cost hydrogeological investigation tool?

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Dr. Bernard Collignon *- collignon urbaconsulting.com*
Urbaconsulting – 198 chemin d'Avignon – 84470 – Chateauneuf de Gadagne – France

The relative movements of the Earth, the Moon and the Sun induce variations in the gravitational field which are reflected, among other things, in ocean tidal phenomena. Similar phenomena affect groundwater.

This signal has often been studied and modelled in coastal aquifers, but there are fewer studies that focus on piezometric tides far from the sea and most of these studies focus on a few isolated wells. The first publications dealt with deep aquifers or oil fields where the piezometric tide has a significant amplitude. Some authors have deduced that piezometric tides only affect confined aquifers.

We tested this hypothesis by systematically studying the tidal signal in shallow and unconfined aquifers. Key finding: the piezometric tidal signal is universal, as are the forces that generate it. If this signal often goes unnoticed, it is simply because other phenomena with a larger amplitude hide it (rain infiltration, barometric effects, stop/go from nearby wells...- Figure 1).

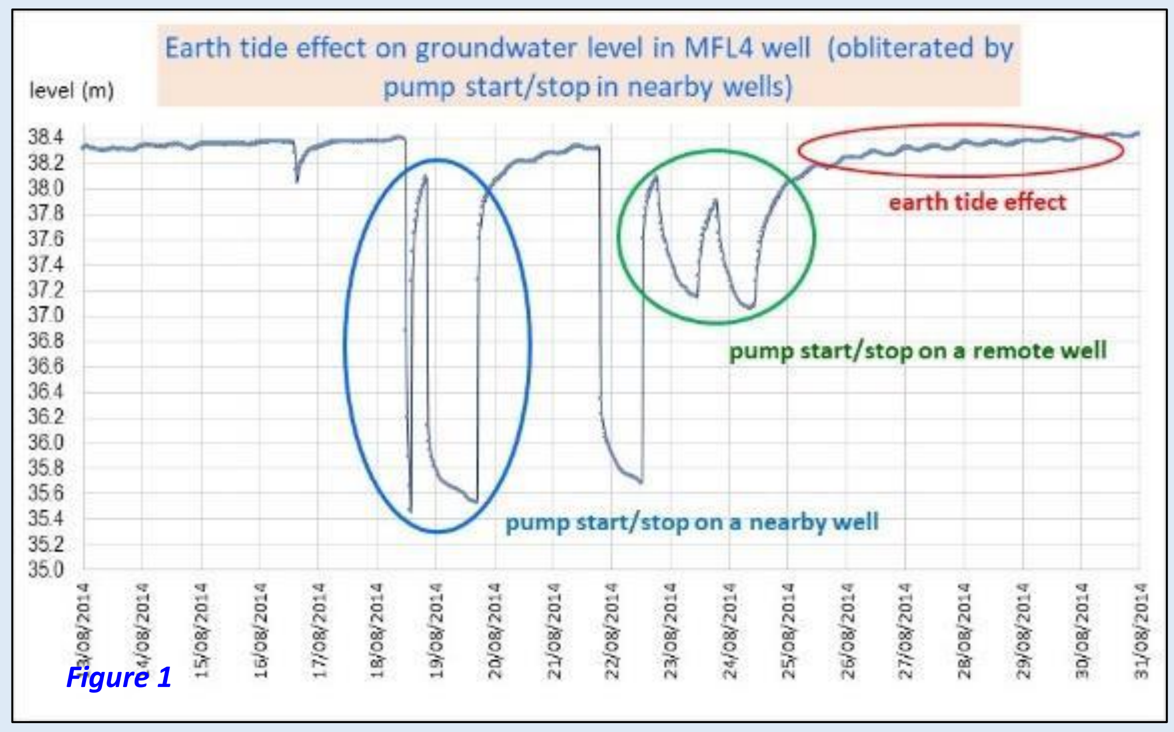


Figure 1

Study areas for tide signal

To study in more detail the piezometric tidal signal in continental aquifers, we have equipped 5 countries in Europe and Africa with drilling measurement instruments (Figure 2).

By implementing an adequate measurement protocol and suitable signal processing procedures, we were able to isolate a piezometric tidal signal in the majority of the boreholes studied. We were then able to carefully analyze the characteristics of this signal (amplitude, phase, shape) and their evolution over time, with depth and from one well to another.

Figure 2

Earth tides and ocean tides

Groundwater is sensitive to two types of tidal effect that have the same astronomical cause (the relative movements of the Earth, Moon and Sun), but fundamentally different hydrogeological mechanisms.

Ocean tides *are the deformation of the hydrosphere caused by the Earth's rotation in the gravitational field of the Moon and the Sun. The vertical deformation of sea levels commonly exceeds one metre and can reach about ten metres in areas where the tidal effect is amplified by the topographic configuration of the seabed (as in Brittany or in the St Lawrence River). Such strong water load variations have a strong impact on coastal aquifers, where they induce periodic alternative flows, from the sea to the aquifer and vice versa (Cazenove, 1971), (Krivic, 1982), (Cuello, et al., 2017). These horizontal groundwater flows in karst aquifers is often leading to greater sea water intrusion than that observed in porous aquifers.*

Earth tides *are the deformation of the Earth's crust following the Earth's rotation in the gravitational field of the Moon and the Sun (Melchior, 1978) (P.Melchior & B.Ducarme, 1989). When the Earth's crust deforms, this generates pressure head disturbances caused by dilatation of the aquifer (Hsieh, et al., 1987). Head disturbances vary with time and space and induce interstitial pressure variations in the aquifer itself, resulting in piezometric level variations (Hsieh, et al., 1987) but limited horizontal groundwater transfers. Oscillations in piezometric levels induced by Earth tides are often of small amplitude. This can make measuring these oscillations difficult because the measuring tools do not have a sufficient sensitivity and tide signals are often obscured by other larger fluctuations (barometric effects, rainfall, pump stop/go in nearby wells, etc.*

The piezometric signal is a signature of the aquifer

It is homogeneous within the same aquifer

Figure 3 – Tide in a semi-confined shallow aquifer in Chad (60-m deep).

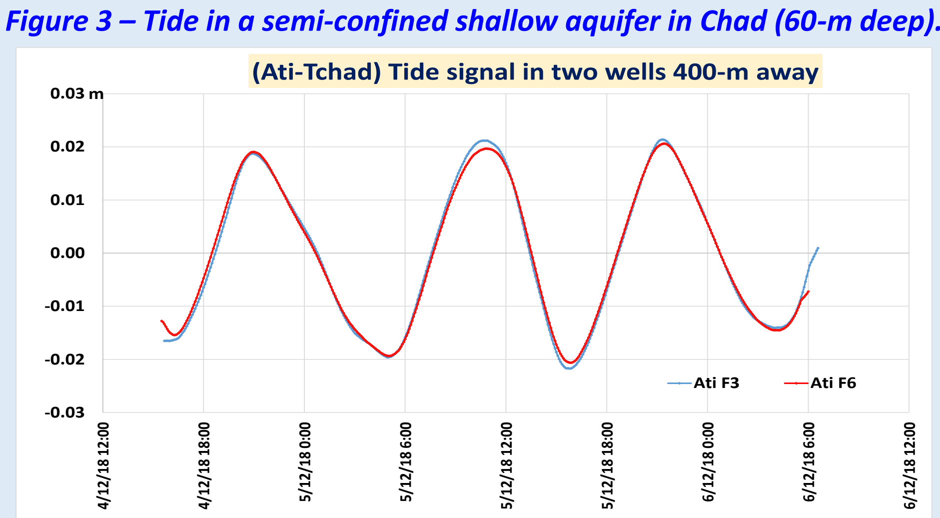
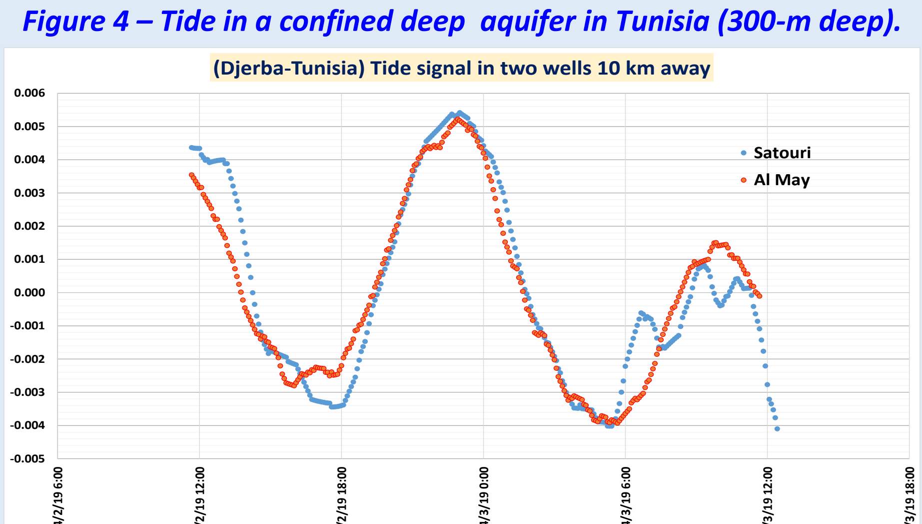


Figure 4 – Tide in a confined deep aquifer in Tunisia (300-m deep).

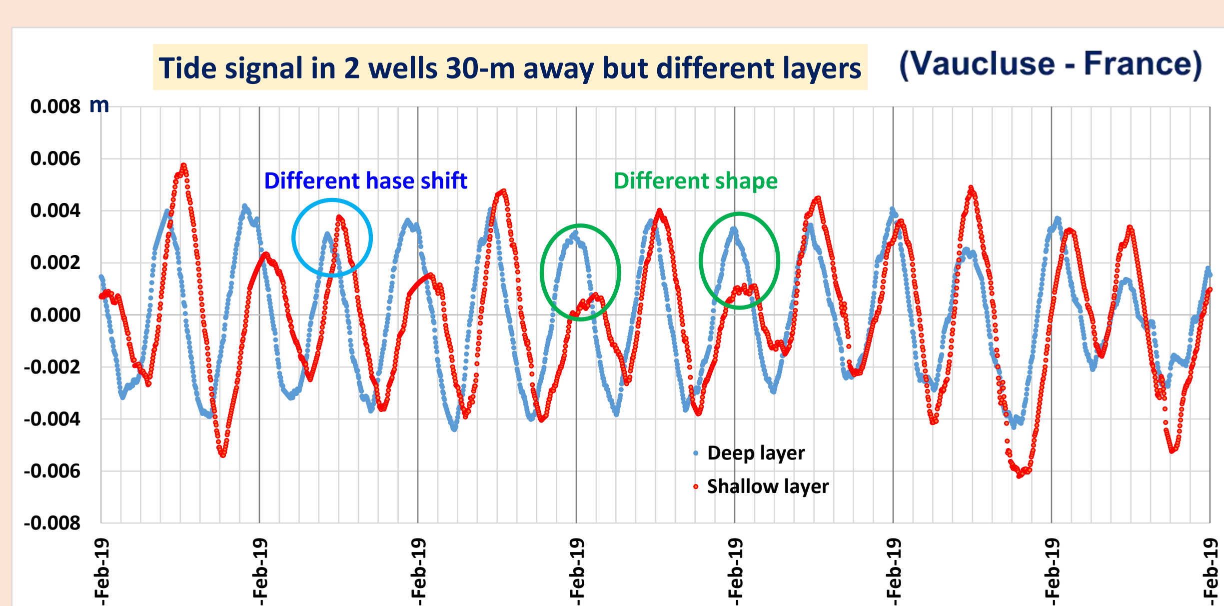


It differs from one aquifer to another in the same place

Figure 5 – Tide in a shallow unconfined aquifer in France

These two neighboring wells capture the same surface aquifer (Plio-Quaternary alluvium), but the first is 11 m deep and only captures the surface layer while the second captures a deeper layer at 38 m depth.

The two tide signals differ by phase shift and signal shape.



What to do with the tide signal?

The features of the tide signal are connected to the capacitive qualities of the aquifer, such as storativity (Hsieh et al., 1987).

This makes it an amazing tool for field hydrogeologists or modelers, who are in dire need of storativity measurements. Indeed, it can only be measured during a pump test if the well is coupled with a piezometer of the same depth, located at a short distance. Such a system is so expensive that the vast majority of operating boreholes do not have one. The hydrogeologist is then reduced to estimating very roughly the storativity from lithology.

The precise study of the tide signal is then an alternative tool for studying the capacitive qualities of aquifers. This requires very accurate piezometric measurements (<1 mm), excellent barometric correction and adequate signal processing to eliminate background noise and other interference (Collignon, 2018).

The accurate study of the tide signal has comparative advantages over conventional methods (such as pumping tests). They can provide valuable information:

- the characteristics of a large portion of the aquifer (unlike pumping tests that mobilize only a limited area around the borehole);
- for a limited cost (no need to invest in a piezometer, or even in a long pumping test);
- without having to manage the discharge of pumped water into the environment

Can we easily model tide signals?

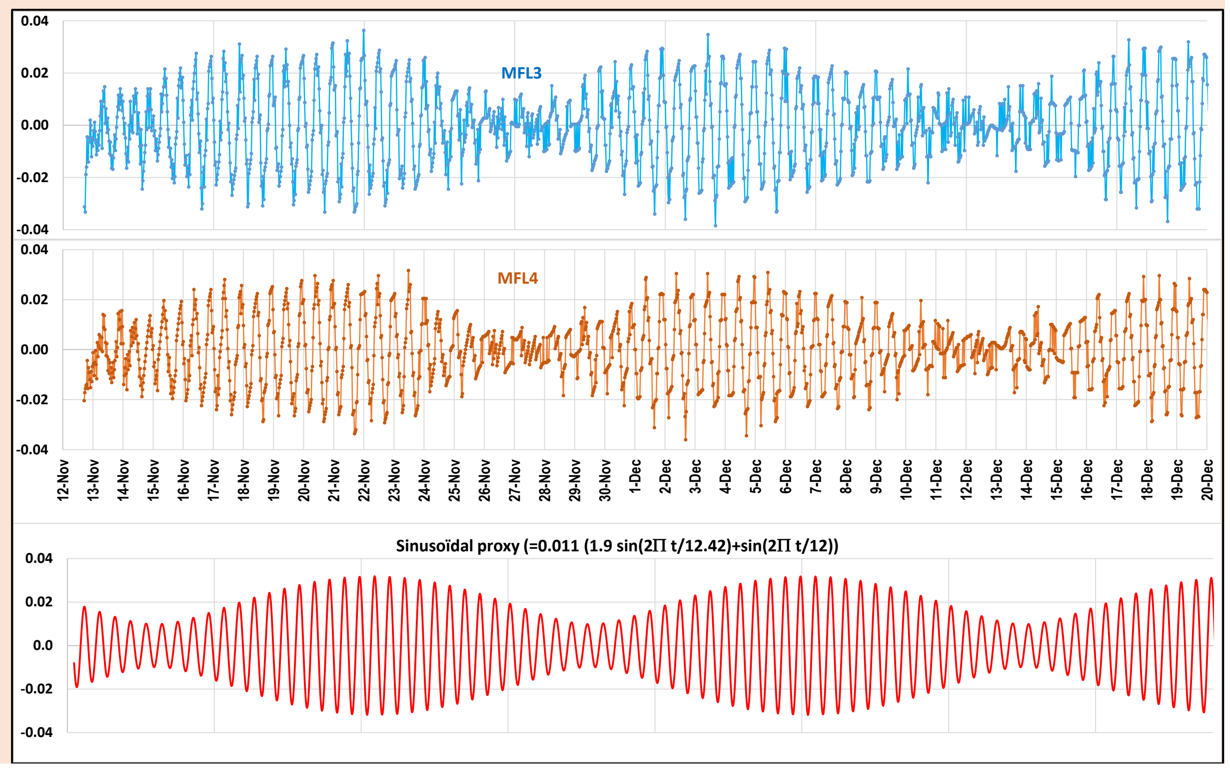
The first tide signal interpretation models were built on the assumption that the signal was simple and could be approximated by a sinusoid (Cazenove, 1971).

In this case, the signal can be characterized by two simple numbers: its amplitude and its phase shift with respect to the movement of the Moon for example (Hsieh et al., 1987) (Rojstaczer, S. & Riley, F., 1990).

The first piezometric tidal signals we studied in Gabon (near the Equator) could indeed be approximated by a simple combination of two sinusoids (corresponding to semi-diurnal lunar and solar tidal waves).

However, subsequent observations at higher latitudes showed that the tidal signal was much more complex.

Figure 6. Sinusoidal proxy of tide effect on groundwater levels (Collignon & Ondo, 2018)



Tide signal complexity

The measurements we have multiplied show that the signal is more complex than a sinusoid or a combination of a limited number of sinusoids:

- The amplitude varies during the lunar month, and it is therefore more relevant to characterize the signal by its maximum amplitude during a lunar month or a sidereal year (Figure 7).

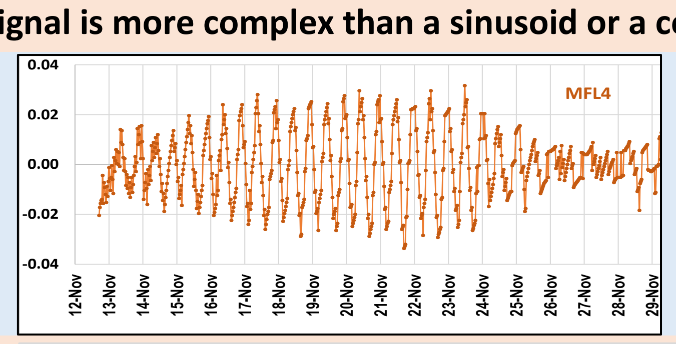


Figure 7. Amplitude varies with time

- The phase shift varies during the lunar month, and it is therefore more relevant to characterize the signal by its phase shift at a specific time in the lunar cycle (for example when the moon and sun are in quadrature) (Figure 8).

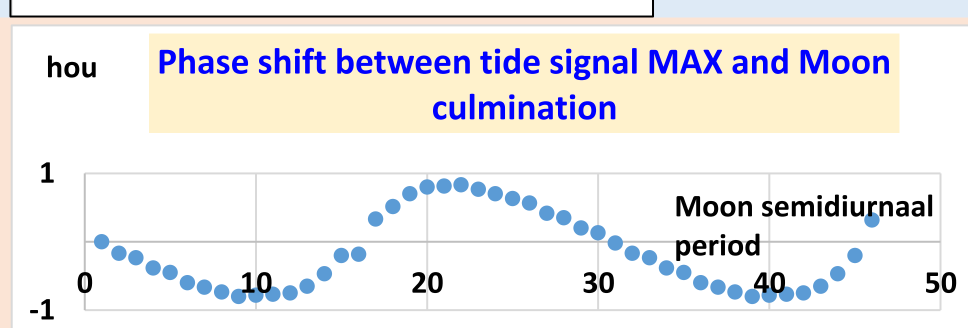


Figure 8. Phase shift varies with time

- The shape of the signal is more complex than a simple sinusoid, because it integrates the effects of several different physical phenomena (Figure 9).

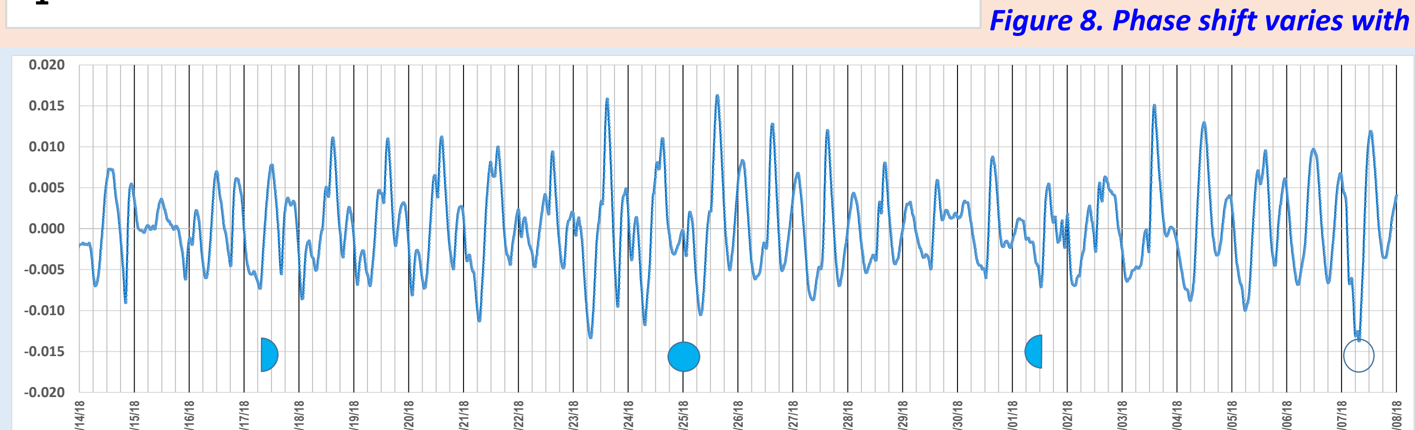


Figure 9. Signal shape is sometimes very complex.

Conclusions and perspectives

The complexity of the piezometric tidal signal should not be considered an insurmountable obstacle. It simply reflects the complexity of the subsoil. The tidal signal is therefore a very rich source of information.

Our current investigations aim to link the rich information of the signal with the properties of the aquifer and its heterogeneities.

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