Micro gravity and cross-hole seismic to monitor water storage changes in aquitards

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SUMMARY

Aquitards surround many aquifers. Due to their comparatively high storage capacity, they will control the hydraulics of aquifers in the long term. Long term management of aquifers therefore requires a good understanding of aquitard characteristics. To quantify water storage changes in an alluvial sequence a micro gravity station has been set up adjacent to an agricultural field in the Liverpool Plains in NSW, Australia. Gravity changes over time will provide an integrated signal of the total water storage changes at the site. Piezometers at the site will allow to determine at which depth the storage change is occurring. To derive water storage changes from the water level changes in the aquitards and confined aquifers at the site, the specific storage (S_s) of the formation needs to be known. Two insitu methods to derive S_s are applied. Firstly, S_s is derived based on the bulk modulus, which is obtained in a cross hole seismic survey and secondly S_s is derived based on pressure analysis in the lysimeters. S_s values derived from the pressure analysis in the lysimeters are one magnitude higher than those based on the cross hole seismic. This difference needs to be further investigated and might be due to the thick unsaturated zone (20 m) at the site, which appears to interfere with the pressure analysis in the lysimeters.

Key words: water storage change, aquitard, micro gravity, electrical resistivity, cross-hole seismic

INTRODUCTION

Insufficient knowledge of the moisture content, total water storage, hydraulic conductivity and water quality of the many aquitards overlying critical groundwater aquifers in Australia is a major threat to groundwater resource security. Aquitards surround many aquifers and due to their comparatively high storage capacity, they will control the hydraulics of aquifers in the long term (Remenda, 2001). Research program 1B of the National Centre for Groundwater Research and Training is directed towards improving our understanding of aquitard hydrology. As part of this program a combination of geophysical techniques (micro gravity, cross-hole seismic, time lapse resistivity surveys and detailed pressure analysis in piezometers) are being used at a field site in the Liverpool Plains.

The use of gravity variations over time to monitor water storage changes at global scale has been significantly improved through the GRACE satellites (Tapley et al. 2004). However, the link between the global water storage changes and water storage at the field scale has not yet been achieved. To provide gravity data at field scale resolution a fixed ground based gravity station has been set up at the field site at the Liverpool Plains. Gravity changes over time provide an integrated signal of total storage changes at the site. However, due to the nature of gravity, the exact sampling volume is difficult to determine (Creutzfeld et al. 2010). To resolve the integrated gravity signal additional measures of soil moisture and groundwater storage are needed. Data from time lapse resistivity surveys, cross-hole seismic and pressure analysis in piezometers at the field site will aid the gravity interpretation. The gravity signal gives the integrated signal of water storage change and the other three methods give an indication of where the change is occurring.

If the porosity of an unconfined aquifer is known, the changes of hydraulic head in a piezometer can directly be related to water storage changes. In aquitards or in aquifers that are confined by an aquitard the interpretation of pressure head variations are less straight forward. Firstly because pressure head variations can not only be caused by changes in water storage in the monitored formation, but also by water storage variations in overlying layers including soil moisture changes in the unsaturated zone (van der Kamp and Schmidt 1997). Secondly, the specific storage of a formation, which is a measure of how much water is released from a formation per meter decrease in pressure head, needs to be known to relate variations in pressure head changes to changes in water storage.

Here the set-up of the micro gravity station on the shrinking and swelling clay soil at the field site is described, together with the use of the cross-hole seismic and pressure analysis in the piezometers to derive the specific storage of the formation.

METHOD AND RESULTS

The micro gravity station was set up at the field site in April 2011 (Figure 1 top). A solar powered insulated hut assures a stable external operation temperature and constant power supply for the g-phone gravimeter (Figure 1 bottom right). To assure noise free gravity data a stable and leveled foundation is crucial. The clay soil at the site is highly reactive and shrinks and swells during drying and wetting periods, resulting in soil level changes of up to 30 cm. To assure that the gravity meter remained stable and leveled during shrinking and swelling of the soil a 10 m deep reinforced concrete foundation (30 cm diameter) was constructed (Figure 1 bottom left). The solar powered hut had a hole cut into the floor before it was placed over the foundation. Finally, the gravity meter was placed on top of the foundation, which sticks into the solar powered hut through the hole in the floor.

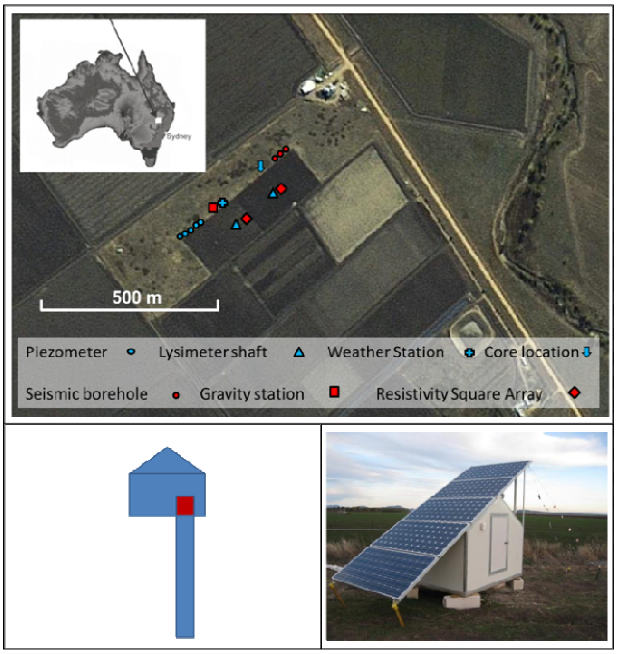

Figure 1: (top) Instrumentation at the field site in the Liverpool Plains; (bottom left) schematic of the foundation for the gravimeter; (bottom right) the solar powered gravity station in the field.

Also installed at the site are pressure loggers in 6 piezometers that log the piezometric water levels at 16, 20, 25, 34, 40 and 54 m depth at the site. The pressure differences in the piezometers were analyzed to determine the barometric efficiency (BE) and loading efficiency (LE) of the formation as well as the specific storage of the aquitard and confined aquifer. Pressure changes in piezometers with high loading efficiency (LE = 1 – BE = 1.0) can be related to changing soil moisture storage (van der Kamp and Schmidt 1997). In addition, the BE allows to calculated the specific storage (S_s) at the screen depth of the piezometer as $S_s = \rho g \Phi \alpha / BE$, where ρ is the fluid density, g is the acceleration due to gravity, Φ is the porosity and α is the fluid compressibility.

The BE values derived based on the pressure analysis in the piezometer (based on the method by Gonthier 2007) and the resulting S_s are given in Table 1. The thick unsaturated zone at the site (~20m) result in relatively large uncertainty in the BE and S_s values, which indicates that pressure analysis might not be the best method to derive S_s at the site. This reasoning is supported by the low pressure response that is observed due to an artificial loading with a 35000 kg drill rig parked above the piezometer screened at 20 m depth. Based on the determined LE this weight should have resulted in a water level rise of >1cm (Gonthier 2007). However, no rise in water level was observed.

Table 1: BE and Ss values calculated based on the pressure analysis in the six piezometers at the site.

Piezometer depth (m)	BE	Ss (10^{-5})
16	0.05 ± 0.01	3.6 ± 0.7
20	0.03 ± 0.01	6.0 ± 2.0
25	0.02 ± 0.02	9.0 ± 9.0
34	0.1 ± 0.05	1.8 ± 0.9
40	0.1 ± 0.05	1.8 ± 0.9
54	0.08 ± 0.05	2.2 ± 1.1

Three 40 m deep seismic boreholes have been installed at the site (Figure 1 top) to allow cross-hole seismic surveys. A cross-hole seismic survey was carried out at the site with measurements taken every meter over the depth of the boreholes. The bulk modulus determined based on the S and P wave velocities can be used to determine depth specific values of S_s through $S_s = \rho g(\beta + \Phi\alpha)$, where β is the compressibility of the porous medium, which is the inverse of the bulk modulus.
The specific storage values derived based on the cross-hole seismic results are shown in Figure 2. Values range between 2 and $9*10^{-6}$, with the majority of value ranging between 2 and $3*10^{6}$, which means that a storage change of 2-3 cm^3 would result in a 1 meter change of pressure head. These values differ by a magnitude from the values that were derived based on the pressure analysis in the piezometers. This difference needs to be investigated further and might be due to the think unsaturated zone at the site.

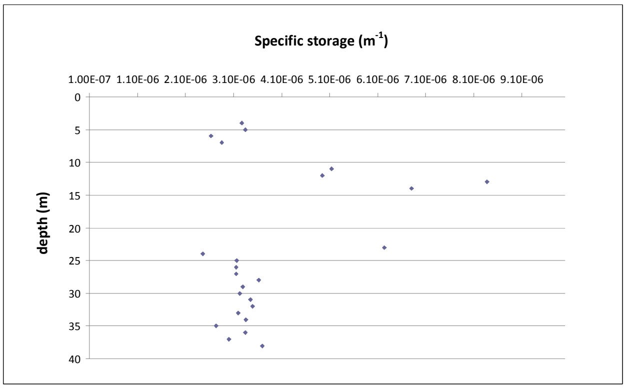

Figure 2: specific storage values determined through cross-hole seismic survey.

CONCLUSIONS

Work at the site, which includes monitoring and further extension of the instrumentation will continue until at least the middle of 2014. To interpret the gravity data that is being collected at the site accurate values of specific storage in the formation are needed. Two alternative field methods to determine specific storage were used. The specific storage values derived with the two methods vary by a magnitude from 10^{-6} m^{-1} to $10^{-5}m^{-1}$. The reasons for this difference need to be further investigate and might be due to the think unsaturated zone at the site.

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