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Detection of a Soil Moisture and Groundwater Signal in Ground-Based Gravity Observations

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Abstract: Gravity observations have the potential to provide an exciting new source of remotely sensed data to constrain the water balance in land surface models. This would result in more accurate soil moisture and flux predictions and correspondingly improved numerical weather prediction and global climate forecasts. However before existing or future (GRACE or GOCE) dedicated gravity satellites can be utilised in an operational setting it must be shown that a soil moisture signal is detectable in gravity observations. This is extremely difficult to show directly for the satellite observations due to the massive spatial scale involved (1000 km^2 or larger depending on accuracy requirements), so a ground-based field study of soil moisture, groundwater and gravity changes is essential in verifying the magnitude of the hydrological signal in gravity observations. This paper presents results from two field sites in the Kyeamba Creek catchment in NSW where soil moisture, groundwater and gravity have been monitored for one year. One is a hillslope site with no groundwater whereas the other is a valley site with a shallow water table. After correcting for earth tides and gravity meter drift, a gravity network adjustment is performed for two time periods chosen to capture the full range of subsurface water storage (autumn and spring). The adjustment improves the precision of the gravity estimates at each site relative to a hydrologically stable bedrock reference site. A t-test is performed on the gravity changes at the two sites and the valley site is found to have a significant change in gravity that corresponds extremely well to the predicted hydrologically induced gravity change. There are many complicating factors in a ground-based study, but nevertheless a hydrological signal (predominantly soil moisture) has been detected in the gravity observations of a valley site with a shallow groundwater table.

Keywords: Soil Moisture, Groundwater, Gravity, Remote Sensing, GRACE.

1. INTRODUCTION

Increasingly gravity is being recognised as an important source of remotely sensed data for hydrological applications at both the field and continental scale. At large spatial scales the current Gravity Recovery And Climate Experiment (GRACE) and future Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellites are able to measure small changes in the earth's gravity field (geoid). At short time scales these changes are predominantly hydrologically induced and can be used in a data assimilation framework to constrain the soil moisture and flux predictions of land surface models (LSM) [Ramillien et al., 2006]. The improved LSM predictions would consequently improve the predictions of numerical weather prediction (NWP) and global climate models (GCM) by providing them with more accurate boundary conditions.

At the field scale ground-based gravity observations can be used to assess the state of deep aquifers without the need for costly and impractical piezometers. If bores already exist gravity data can be used to determine the specific yield of the aquifer [Pool & Eychaner, 1995]. Additionally the gravity data provides change in mass of the whole profile (not just the aquifer) and can give an indication of recharge rates [Van Camp et al., 2006].

However before gravity data can be fully exploited in a hydrological framework it is necessary to understand the limitations of the method and requirements for high accuracy, as well as determine the magnitude of the hydrological signal that is detectable in field based gravity data. This paper addresses the last issue.

2. EXPERIMENTAL DESIGN

A number of soil moisture and groundwater monitoring sites were installed in the Kyeamba Creek Catchment NSW (southeast of Wagga Wagga) in 2002 to complement an existing network throughout the Murrumbidgee River Catchment. At each of the sites three CS616 water content reflectometers were vertically installed to cover the depths 0–30, 30–60 and 60–90 cm. Time Domain Reflectometry (TDR) rods were inserted to field calibrate the CS616

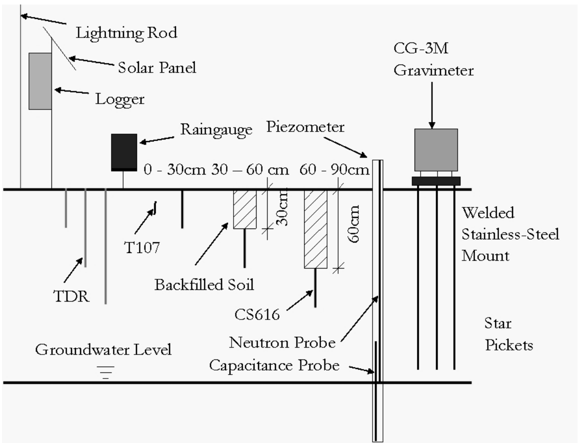

Figure 1: Schematic of a typical field site. Time domain reflectometry (TDR) probes are 30, 60 and 90 cm long, capacitance probe is removed when using NMM, groundwater was not reached at all sites.

sensors. A shallow piezometer was installed with a 2 m capacitance probe to monitor groundwater. This PVC tube also doubles as an access tube for periodic neutron moisture meter (NMM) measurements taken to the depth of the water table or bottom of the bore. Steel pads for the gravimeter were installed as close to the soil surface as possible but on stable 2 m star pickets inserted to depth of refusal. The pad was designed as a cut out triangle to allow as much precipitation and evapotranspiration to pass as possible while maintaining maximal rigidity. A schematic of the instruments at each site is shown in Figure 1. Further details including the site locations can be found in Smith et al. [2005].

Four sites were chosen to check if hydrological changes on hillslopes would be detectable by gravity both in the presence and absence of groundwater. Results are presented here for two of those four sites (a valley site with, and a hillslope site without groundwater). Additionally a bedrock reference site was chosen as a hydrologically stable benchmark. All sites were sampled in both dry and wet conditions (autumn and spring 2005).

Gravity may be measured by a variety of gravimeters manufactured by a small number of companies. These meters can be distinctly classified as giving either a relative or absolute measurement of gravity. Absolute measurements are desirable, but the meters have low accuracy and are not field portable. Relative (spring) gravimeters are field portable and very accurate but the sensor suffers from a large drift in apparent gravity value. Therefore when relative meters are used for high precision micro gravimetry, the drift needs to be accurately accounted for and the calibration of the meter is crucial. The Scintrex CG-3M was chosen because it was the most accurate field portable, rugged gravimeter at the time [Smith et al., 2005] More information on the performance of this meter can be found in (Smith et al., in preparation).

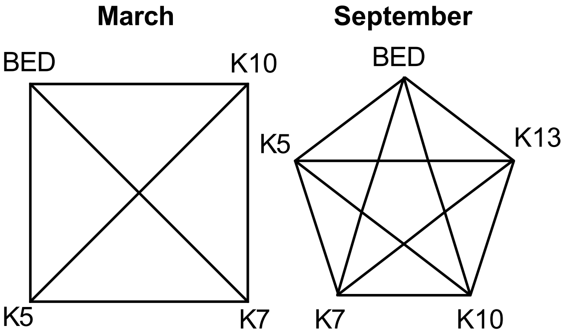

Figure 2: Gravity networks for March and September 2005.

The gravity observation at a site is a function of both meter behaviour and gravity. The gravity values reported by the meter vary linearly with time due to drift (extension) of the spring sensor. Additionally there is a short term post-transport stabilisation period where the gravity changes nonlinearly with time. Both of these effects are instrument artefacts and are corrected by differencing gravity observations between sites. The drift is also estimated during network adjustment. In addition to changes in water storage, real temporal changes of gravity occur due to variations in earth tides, ocean tides, atmospheric pressure and earthquakes. Tide and pressure effects can be corrected for prior to network adjustment However, earthquakes must be screened for by keeping a log of all earthquakes during the gravity survey (from http://www.ga.gov.au/bin/listQuakes) and performing an outlier detection test during the network adjustment.

A sampling strategy was chosen to construct a complete homogeneous network in which each site is connected to every other site (complete) by the same number of ties (homogeneous). This is shown in Figure 2 where a line connecting one site to another is referred to as a tie and represents one day of measurements (typically 8 differences). By forming ties (i.e. measuring gravity at first one site and then another in quick succession) gravity differences can be established. The ties with the bedrock site (BED) can be used directly to determine the gravity at a soil moisture monitoring site relative to the hydrologically stable reference site, but the other ties (e.g. K5 – K7 in March) can also be used in conjunction with the BED ties to form closed loops (BED – K5 – K7). The differences in these closed loops should sum to zero. By enforcing this zero sum condition outliers can be detected and the network can be strengthened by distributing the standard error at weak ties (e.g. BED – K5 where both sites do not have good wind protection) throughout the network. This is done within the framework of a Gauss-Markov Model [Hwang et al., 2002].

3. GRAVITY OBSERVATIONS

Gravity observations made at each site consist of eight consecutive 2.5 minute samples which are averaged (to improve accuracy). The individual samples are represented as

$$\begin{aligned} z(t) = g + B & \\ +E(t) + P(t) & \\ +D(t) + S(t_s) + \varepsilon, & \end{aligned} \quad (1)$$

where t is the time of the gravity observation, z is the gravity reported by the gravity meter (in nms^{-2}), g is the desired gravity that is dependent on elevation (static) and hydrological changes (dynamic), B is a bias constant across all sites (due to the relative meter), E is the combined effect of earth and ocean tides and loading, P is the pressure effect, D is the gravimeter drift, S is the post transport stabilisation effect, t_s is the time since the start of the measurement and ε is a random error (assumed Gaussian).

The three lines of equation (1) represent the site dependent, environmental and gravimeter effects respectively. The site unknown gravity g is sought, B is unknown but assumed constant, $E(t)$ is removed via an earth tide model, $P(t)$, $D(t)$ and $S(t)$ are modelled and removed with the following equations.

For the pressure correction

$$P(t) = C\left(p - p_n\right), \quad (2)$$

where p is measured barometric pressure (hPa) and p_n is normal atmospheric pressure modelled by

$$p_n = 1013.25\left(1 - \frac{0.0065\,H}{288.15}\right)^{5.2559}, \quad (3)$$

where H (m) is station elevation [Torge, 1989]. C is an admittance constant that is theoretically between 3 and 4 but is both site and instrument specific. C was calculated for this instrument from a laboratory analysis of gravity and pressure and found to be 3.93 (±0.45).

The meter drift is modelled for medium time periods (hours to days) by a polynomial

$$D(t) = \sum_{p=1}^{order} d_p \left(t - t_0\right)^p, \quad (4)$$

where d_p is the coefficient of the drift for order p, t is time and t_0 is an arbitrary initial time. However quadratic ($order$ = 2) or linear drift usually suffices. A linear drift coefficient (d_1) is determined over a 12 or 24 hour time period (corresponding to the principal earth tides) in the laboratory before and after each 1–2 week field campaign, and checked in the field by measuring the bedrock site at the beginning and end of every day. After the survey the coefficients of equation (4) are estimated (with t_0 as the start of the survey) while performing a network adjustment on all the gravity differences (over the 1–2 week period). This estimate is an average value for the whole survey (i.e. it is assumed the drift is stationary over this period).

The data points for every measurement at a site were plotted and the seven differences between successive 2.5 minute samples found to follow a natural logarithm. This model gave an R^2 of 0.979 for the average of the 5 sites. Therefore the post transport stabilisation effect was not removed at each site. Rather, the effect was cancelled out by differencing the gravity at sites.

4. GRAVITY NETWORK ADJUSTMENT

Network adjustment statistically adjusts the gravity at each site by distributing the errors to ensure the sum of the differences between any three sites is zero (i.e. $(g_1 - g_2) + (g_2 - g_3) + (g_3 - g_1) = 0$, where g_i is the gravity at site i). This results in increased precision of the observations (due to use of more than one observation for the estimate). However it also introduces correlation between the observations for the same reason.

A global model test is used to check the model is complete and consistent with the field data. If this test fails it is either due to inadequacies in the model or the data. To check the data for gross errors, outlier detection is performed on the model residuals. Outlier detection depends on assumptions being made about the residual distribution, therefore the normality of residuals also needs to be tested. If no observations are detected as outliers and the global model test still fails (assuming the numerics are robust) it must be due to a failing in the model structure. This could be due to a systematic error in either the deterministic or stochastic components of the model (equation (1)). Deterministic errors can be an oversimplified polynomial representation of drift behaviour, neglected environmental parameters (barometric pressure and air temperature), or lack of preprocessing to remove post-transport drift. Stochastic errors are usually caused by over generous representation of observational accuracy, but can also be caused by neglect of observation correlation or misspecification of error distribution.

Network adjustment was performed on four and five sites at two epochs (Figure 2); the results are summarised in Table 1. Note that the gravity differences between any three sites in Table 1 necessarily sum to zero after network adjustment compared to an average three station loop misclosure of 40 nms^{-2} and 100 nms^{-2} for the two epochs prior to adjustment. The network adjustment was performed with a free network constraint (i.e. relative to a site), with BED as the constraining site. Details on the network adjustment procedure can be found in [Hwang et al., 2002]. A base case approach was followed where drift was modelled as linear ($order$ = 1 in equation (4)), the pressure effect on gravity was ignored (C = 0 in equation (3)), and earth tides were simply removed by an old model within the gravity meter [Longman, 1959]. Better results are expected by modelling the drift as linear but separately for each day (rather than an average over the whole survey campaign of approximately 2 weeks), removing the pressure effect with field pressure data, and removing the earth tides by using the nearby (100 km east) Mt Stromlo superconducting gravimeter data or using a newer earth tide model [Cartwright & Tayler, 1971; Cartwright & Edden, 1973]. Despite this, a base case approach is essential to assess the most significant corrections needed to achieve highly accurate results. The base case model passed the global model test and no outliers were detected.

A t-test (unequal variance) was performed on the site gravity estimates for each epoch. The results are shown in Table 2, where a significance level of 0.05 was chosen and the degrees of freedom (dof) are the sum of the dof for March (45) and September (74). It is assumed that no change in the gravity occurs at BED (the bedrock benchmark site) There is a significant positive change in gravity at K7 of 85.4 nms^{-2}, a reasonable, but insignificant positive change at K10, a large but insignificant negative change at K5 of 31.9 nms^{-2}, and no result for K13 as it was not measured in March. A positive change (due to increased terrestrial water storage) was expected at all sites, except perhaps K5 (the hillslope site) where the gravitational effect of upslope moisture (a reduction) could cancel the gravitational effect of moisture underneath the meter (an increase).

Table 1: Gravity and standard error for each site relative to the hydrologically stable bedrock after a network adjustment, all units nms^{-2}.

	March 2005		September 2005	
Site	**Gravity**	**Error**	**Gravity**	**Error**
BED	0	13.6	0	20.3
K5	83511.0	14.1	83479.1	20.3
K7	112643.4	13.9	112728.8	20.0
K10	165453.2	13.8	165465.0	19.9
K13	N/A	N/A	124139.4	20.0

5. ANALYSIS OF GRAVITY AND HYDROLOGICAL CHANGES

Precipitation, soil moisture and groundwater were measured continuously at all sites. Neutron moisture meter (NMM) counts were also taken at the time of the gravity surveys to establish the variation of soil moisture in the zone below the installed soil moisture sensors (90cm). Two sites are presented here, K5 and K7. These were selected prior to the network adjustment on the basis that the pair represents a contrast between hillslope and valley as well as deep and shallow groundwater respectively. Coincidentally they were also the two sites that had the largest gravity changes between March and September (Table 2).

Both sites are used for cattle grazing and are duplex soils covered with grass. K5 has an available water capacity (AWC) of about 20% vol/vol and no water table within the shallow bore of 1.7 m depth, whereas K7 has an AWC of about 25% vol/vol and a water table that varies between 2.2 and 4.7 m, with a bore depth of 9.4 m. The NMM counts for K5 and K7 in March and September 2005 are shown in Figure 3. Both the March and September K7 counts stop at the water table (higher in September), the K5 counts stop at the bottom of the piezometer. There is little change in the

Table 2: t-test results for site differences of average gravity (nms^{-2}) for the two epochs. Significance level of 0.05 and 119 degrees of freedom.

Site	Gravity Difference	Test Statistic	Critical t Value
BED	0	0	1.98
K5	-31.9	1.29	1.98
K7	85.4	3.52	1.98
K10	11.8	0.48	1.98
K13	N/A	N/A	N/A

count ratio at depth (below 90 cm) for K5, so the soil moisture change can be considered to be predominantly in the monitored zone (0-90 cm). There is more change at depth for K7 but it is assumed the bulk of the soil moisture change is captured by the CS616 sensors.

Hydrological changes can be converted to a predicted change in gravity by using a simple Bouger slab model [Telford et al. 1990]. A change in mass is converted to a change in gravity by assuming the mass is distributed as a horizontal sheet with infinite extent. This assumption is well suited to soil moisture and groundwater at flat sites, but the horizontal requirement is not met for hillslope sites.

For groundwater the Bouger slab model is

$$g_{\text{Groundwater}} = 419.2\, S_y H, \qquad (5)$$

S_y is specific yield, and H is the water table height (positive upwards) relative to some datum. Similarly for soil moisture

$$g_{\text{Soil Moisture}} = 419.2\theta D, \qquad (6)$$

where θ is volumetric soil moisture, and D is the depth the soil moisture is integrated over.

Using the Bouger slab model for soil moisture, the gravity contribution over time of each soil moisture sensor was calculated (Figures 4 & 5). Additionally the groundwater component of the gravity at K7 was computed using an assumed specific yield of 0.05, which is considered reasonable for the alluvial sediment aquifer that this bore lies in [Cresswell et al., 2003]. The water table condition below the bottom of the K5 bore (1.5 m) is unknown, however Cresswell et al. [2003] state that the Kyeamba Creek catchment groundwater system consists of a shallow unconfined valley alluvial sediment aquifer overlying an intermediate scale fractured bedrock aquifer of specific yield around 0.01. The fractured bedrock (granite) aquifer is thought to cover most of the catchment.

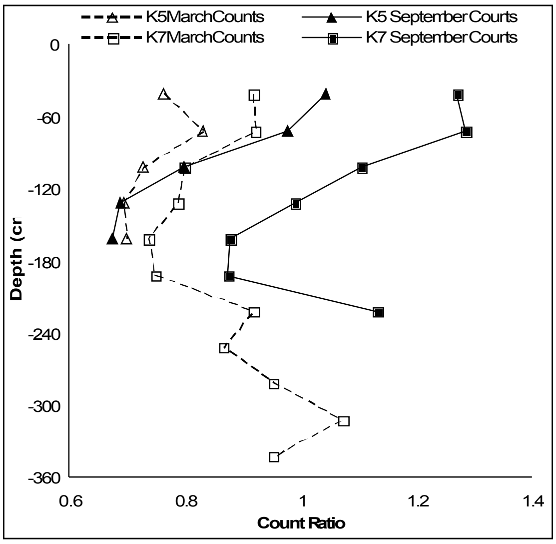

Figure 3: Neutron probe count ratios (relative to background radiation) at K5 and K7, March and September 2005.

The March gravity observation in Figures 4 and 5 is an average of the 9 days of the gravity survey, it is located at the midpoint of the survey. The point is vertically shifted to equal the Bouger slab predicted gravity at that time at each site. Similarly the September observation is an average of 15 days and is also located at the midpoint of this time period, it is plotted relative to the March observation. It should be noted that it rained heavily halfway through the September survey (31 mm of precipitation was

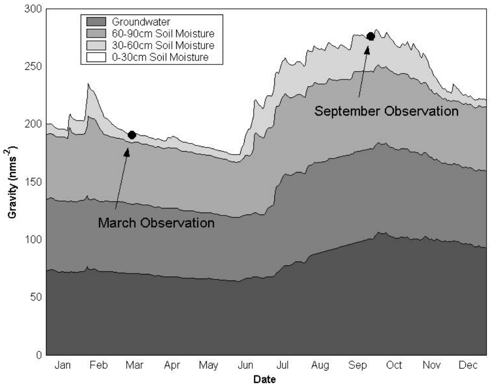

Figure 4: Observed and predicted gravity at K7 using Bouger slab model with continuous soil moisture and groundwater observations.

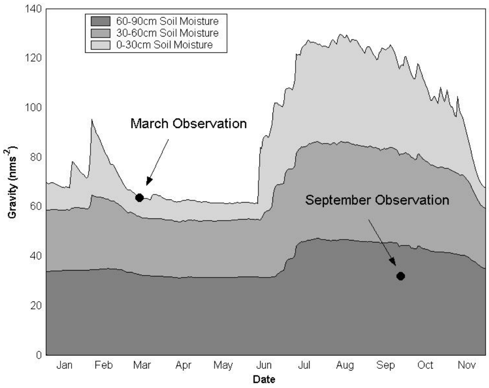

Figure 5: Observed and predicted gravity at K5 using Bouger slab model with continuous soil moisture observations.

recorded in 21 hours at K7). This can be seen by the small peak in the modelled gravity to the right of the sample point in Figure 4. Despite this the agreement between the modelled and observed gravity at K7 is excellent (observation only 3.1 nms^{-2} greater than predicted). This difference of 3.1 nms^{-2} is equivalent to a 7.4 mm error in the estimate of terrestrial water storage change for the whole profile, or a 3.8% relative error.

Unexpectedly the observed gravity at K5 has decreased markedly (but not statistically significantly at the 0.05 level). The September observation for K5 is 31.8 nms^{-2} less than the March observation, compared with a predicted increase of 53.3 nms^{-2}. The reasons for this are unclear, and this site will be the subject of further investigation.

6. CONCLUSIONS

A field based experiment was set up to determine if a change in terrestrial water storage (soil moisture and groundwater) could be detected in ground based relative gravity data. Soil moisture and groundwater monitoring equipment and gravity pads were installed throughout the Murrumbidgee River Catchment. Gravity surveys were performed in autumn and spring of 2005 (dry and wet conditions) at four sites in the Kyeamba Creek Catchment chosen to give a good contrast of site characteristics (hillslope, valley, shallow groundwater and no groundwater). These surveys consisted of many gravity measurements at all sites as well as at a hydrologically stable bedrock reference site at the beginning and end of every day to control gravity meter drift. The gravity at each location was differenced with the gravity measurement preceding and following to form a series of ties that were statistically adjusted to ensure the gravity observations were consistent and precise. A t-test was conducted on the estimated gravity at each site for the two epochs to establish whether a statistically significant change in gravity had occurred. The terrestrial water storage had increased over this time but contrary to expectation there was an insignificant (at the 0.05 level) decrease in gravity at the hillslope site K5, the cause of the decrease is unknown at present. A significant increase in gravity was detected at K7 (a valley site with groundwater between 2.2 and 4.7 m of the surface). The observed change in gravity at K7 corresponded extremely well with the change predicted by the Bouger slab model using the soil moisture and groundwater data, with a difference of only 7.4 mm (or 3.8% relative error) over the profile.

7. REFERENCES

Cartwright, D. and R.J. Tayler, New computations of tide-generating potential, *Geophysical Journal of the Royal Astronomical Society*, 23(1), 45-74, 1971.

Cartwright, D. and A.C. Edden, Corrected tables of tidal harmonics, *Geophysical Journal of the Royal Astronomical Society*, 33(3), 253-264, 1973.

Cresswell, R.G., W.R. Dawes, G.K. Summerell, G.T.H. Beale, N.K. Tuteja, G.R. Walker, Assessment of Salinity Management Options for Kyeamba Creek, NSW: Data Analysis and Ground Water Modelling, Murray Darling Basin Commission, Canberra, 2003.

Hwang, C., C. Wang, and L. Lee, Adjustment of relative gravity measurements using weighted and datum-free constraints, *Computers & Geosciences, 28*(9), 1005–1015, 2002.

Longman, I.M., Formulas for computing the tidal accelerations due to the moon and the sun, *Journal of Geophysical Research*, 64(12), 2351–2355, 1959.

Pool, D.R. and J.H. Eychaner, Measurements of aquifer-storage change and specific yield using gravity surveys, *Ground Water*, 33(3), 425-432, 1995.

Ramillien, G., F. Frappart, A. Güntner, T. Ngo-Duc, A. Cazenave, and K. Laval, Time variations of the regional evapotranspiration rate from Gravity Recovery and Climate Experiment (GRACE) satellite gravimetry, *Water Resources Research*, 42, W10403, doi:10.1029/2005WR004331, 2006.

Smith, A.B., J.P. Walker, A.W. Western, and K.M. Ellett, Using ground-based gravity measurements to monitor changes in terrestrial water storage, paper presented at 29th Hydrology and Water Resources Symposium, Engineers Australia, Canberra, ACT, February 21–23, 2005.

Telford, W.M., L.P. Geldart, and R.E. Sheriff, *Applied geophysics*, 2nd edn, Cambridge University Press, 770 pp., Cambridge, 1990.

Torge, W., *Gravimetry*, Walter de Gruyter, 465 pp., Berlin, 1989.

Van Camp, M., P. Meus, Y. Quinif, O. Kaufman, M. Van Ruymbeke, M. Vandiepenbeeck, and T. Camelbeeck, Karst aquifer investigation using absolute gravity, *Eos Trans. AGU*, 87(30), 298, 2006.

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