A framework for assessing the potential of remote-sensed gravity to provide new insight on the hydrology of the Murray-Darling Basin*

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SUMMARY: Achieving a successful long-term strategy for sustainable water resource management of the Murray-Darling Basin (MDB) requires improvement in understanding of the integrated hydrological system and assessing the impacts of land use and climate change on this system. The recent launch of a satellite mission called GRACE (Gravity Recovery and Climate Experiment) has the potential to lead to new insight on the hydrology of the MDB. By observing changes in the earth's gravity field at unprecedented accuracy, the GRACE mission is now providing the first-ever observations of changes in total water storage occurring within the earth's major river basins. This paper outlines the possible applications of GRACE to the MDB and presents a framework designed to assess the overall utility of this novel satellite observation. The framework integrates hydrological modelling and data assimilation techniques with ground-based monitoring of water storage components (e.g. soil moisture and ground water). Early results from this framework indicate that GRACE should provide a statistically significant measure of water storage change across the MDB. Comparisons of modelling results to ground-based measurements from the Murrumbidgee catchment illustrate the potential for GRACE to directly improve model prediction by way of data assimilation methods.

1 INTRODUCTION

The Murray-Darling Basin (MDB) is one of the world's major river systems with a drainage area of approximately 1 million km^2 or 14% of the Australian continent (MDBC 2003). Despite naturally high aridity and low runoff relative to other major river basins (McMahon et al. 1992; MDBC 2003), agricultural production within the MDB accounts for approximately 40% of the total production in Australia (DAFF 2005). This high level of agricultural output has been achieved through a combination of irrigation (~ 75% of the total water used in Australia) and extensive clearing of native vegetation for cropping and pastoral land use (MDBC 1999; DAFF 2005).

It is now recognised that dramatic alteration of the MDB landscape and river systems since the time of European settlement has led to several undesirable effects, including increased salinity, diminished biodiversity and ecosystem degradation (MDBC 1999; Young 2001). From an economic perspective the issue of salinity is particularly damaging as it threatens not only the health of natural ecosystems but also agricultural production, the quality of drinking water, and the structural integrity of buildings and roads (Hatton 2003). In New South Wales alone over 500 000 hectares of land were estimated to be impacted by salinity in the year 2000 with a projection of 2–4 million hectares by 2050 if changes in land use are not enacted (DLWC 2000).

Achieving a successful long-term strategy for sustainable water resource management in the MDB requires improvement in understanding of the integrated hydrological system and the development of reliable methods for assessing the impacts of land use and climate change on this system. This paper examines the potential for a new satellite mission called GRACE (Gravity Recovery and Climate Experiment) to provide valuable new insight on the

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hydrology of the MDB. The paper begins by outlining the various applications for which GRACE may prove useful in the MDB, and provides the basis for the relation between gravity observations and hydrological processes. The bulk of the paper is devoted to presenting a framework designed to assess the overall utility of GRACE in the MDB. Some early results from this framework are then presented which illustrate the likelihood for GRACE to provide novel contributions.

2 THE POTENTIAL OF GRACE

The goal of the joint NASA and German Aerospace Centre GRACE mission is to accurately map the earth's gravity field on a near-monthly basis for a minimum duration of 5 years (Tapley et al. 2004a). Since hydrological processes are the primary source of temporal variations in mass (and therefore gravity) over land, changes in the total water storage of major river basins can now be inferred from GRACE observations (Wahr, Molenaar & Bryan 1998). Thus GRACE will provide the first-ever observations of total water storage (the integrated product of soil moisture, ground water, surface water and snow) over the entire MDB; measurements which allow an unprecedented assessment of the monthly, seasonal, and inter-annual evolution in water storage at the whole-of-basin scale.

Owing to the dominance of ground water variations in inter-annual storage changes, GRACE has the potential to help assess the effectiveness of recent revegetation efforts for reducing ground water recharge and the subsequent impacts of salinity. Knowledge of ambient storage conditions could also aid in water resources management (i.e. reservoir operation) and directly improve weather forecasts through more accurate model initialisation (Zhang & Frederiksen 2003). In addition, combining GRACE with available observations of precipitation and streamflow allows closure of the water balance at the basin scale thus providing an important and novel estimation of evapotranspiration flux (Rodell et al. 2004).

Another potentially valuable aspect of GRACE is the ability to provide a new measure for assessing the uncertainty in hydrological models of the MDB region (Ellett et al. 2005). Moreover, GRACE may provide a means for directly improving model prediction in the MDB by way of data assimilation techniques (Ellett et al. 2004). To determine the extent to which GRACE may contribute in the MDB, it is necessary to first examine more fully the relation between gravity and hydrology.

3 GRAVITY AND HYDROLOGICAL PROCESSES

The acceleration due to gravity at the earth's surface g is not a constant 9.8 m/s^{-2} but rather varies both spatially and temporally as a function of several parameters including lunar and solar tidal effects on both water and the solid earth, latitude, elevation, topography, subsurface density, post-glacial rebound and the redistribution of mass due to hydrological processes (Telford, Geldart & Sheriff 1990). This is evident when combining Newton's Laws of gravity and motion to derive the equation for g on a body at the earth's surface,

$$g = \gamma\left(\frac{m}{r^2}\right)R \tag{1}$$

where γ is the universal gravitational constant (6.672 x 10^{-11} N m^2 kg^{-2}), m (kg) is any mass affecting the acceleration of the body (predominantly the mass of the earth), R is the unit vector directed towards m and r is the distance between the centres of mass. For a given location at the earth's surface, changes in the gravity field are dominated by changes in terrestrial water storage following the systematic correction for tidal, atmospheric and oceanic effects (Tapley et al. 2004b). The relation between changes in gravity and water storage can be calculated by using the Bouguer slab approximation (Telford, Geldart & Sheriff 1990),

$$\Delta g = 2\pi\gamma\rho b \tag{2}$$

where ρ is density (g cm^{-3}) and b is slab thickness (cm). Assuming the density of water as 1.00 g cm^{-3} leads to the following relation (Pool & Eychaner 1995):

$$\Delta S = 0.419\Delta g \tag{3}$$

where storage change ΔS is in units of cm of water and gravity change Δg is in units of microGal (10^{-6} cm s^{-2}). From (3) it can be seen that the infiltration of ~ 24 mm of rainfall, or a rise in the water table of ~ 12 cm (assuming specific yield = 0.2) would cause an increase in the local gravity field of 1 μGal.

Early work by Lambert and Beaumont (1977) used a field-based gravity meter to detect a correlation between ground water table fluctuations and temporal changes in the earth's gravity field. Recent studies have since demonstrated the effectiveness of this method in monitoring fairly large changes in ground water storage resulting from both natural and artificial recharge to the saturated zone (Pool & Eychaner 1995; Howle et al. 2003). In work related to our current study, Smith et al. (2005) investigated the ability of ground-based gravity meters to also monitor changes in soil moisture storage.

Hydrologically induced changes in the earth's gravity field have also been shown to affect the orbital motion of satellites (Gutierrez & Wilson 1987). Such studies led NASA and the German Aerospace Center to develop the GRACE satellite mission in order to measure precise changes in the earth's gravity field, which in turn can be used to infer large-scale hydrological processes.

The near-polar orbiting twin GRACE satellites were launched in March 2002 with a minimum project life span to 2007 (Tapley et al. 2004a). The novel design of GRACE, employing twin satellites in tandem orbits and an advanced inter-satellite microwave ranging system allows it to monitor the long-to-medium wavelength components of earth's gravity field at much greater accuracy than its predecessor mission called CHAMP – CHAllenging Minisatellite Payload (Reigber et al. 2002). GRACE satellite positions, accelerations and the distance of separation between the satellites are monitored continuously during 16 daily orbits and are inverted to calculate the Stokes coefficients representing optimal solutions to the spherical harmonic expansion of the global gravity field (Wahr, Molenaar & Bryan 1998). Changes in mass over major river basin size areas can then be calculated to an estimated accuracy of ~1 cm of water thickness by relating changes in surface mass density $\Delta\sigma$ to differences in the monthly varying sets of Stokes coefficients (Wahr, Molenaar & Bryan 1998; Swenson, Wahr & Milly 2003),

$$\Delta\sigma(\theta,\phi) = \frac{a\rho_{ave}}{3}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\frac{(2l+1)}{(1+k_l)}\tilde{P}_{lm}(\cos\theta)$$
$$(\Delta C_{lm}\cos(m\phi) + \Delta S_{lm}\sin(m\phi)) \tag{4}$$

where θ is colatitude, ϕ is east longitude, a is the mean radius of the earth, ρ_{ave} is the average density of the earth, k_l are the load love numbers corresponding to the underlying solid earth's deformation to the surface mass loads, $\tilde{P}_{lm}$ are normalized associated Legendre functions and C_{lm} and S_{lm} are the Stokes coefficients provided by GRACE to degree l and order m of ~ 100.

The pre-launch estimate of uncertainty in monthly GRACE observations for the MDB was around 4 mm (Rodell & Famiglietti 1999). Based on the first results from GRACE reported by Wahr et al. (2004) a conservative upper bound of the uncertainty is perhaps 15 mm, though the GRACE instrument errors have decreased over the course of the mission (Tapley et al. 2004a, 2004b). For further information the reader is referred to the GRACE project website at: http://www.csr.utexas.edu/grace.

4 A FRAMEWORK FOR ASSESSING THE UTILITY OF GRACE IN THE MDB

From the earlier discussion it is clear that there are a number of ways in which GRACE may contribute towards a better understanding of the hydrology of the MDB. To provide a comprehensive assessment of the overall utility of GRACE, a framework has been developed which includes three general components: (1) basin-wide hydrological models with explicit representation at the catchment scale, (2) methods for data assimilation of GRACE observations to directly improve model prediction and (3) development of a ground-based monitoring network as a means of verifying the effectiveness of GRACE data assimilation, as well as providing a measure for comparison of GRACE observations to *in situ* measurements.

4.1 Hydrological modelling

Hydrological models at the spatial scale of the MDB can typically be classified as either rainfall-runoff models or land surface models. Rainfall-runoff models generally use conceptual bucket-type approaches to simulate water-balance processes at the catchment scale with accurate results often achieved by way of calibration against stream gauge data. Land surface models (LSM) parameterise both water and energy balance calculations, often in a notionally physically-based manner, and are used to simulate the terrestrial hydrological process interactions within larger numerical weather prediction models or atmospheric general circulation models.

Earlier work by Chiew, Pitman & McMahon (1996) found that both of these modelling approaches gave somewhat similar results in two hydrologically diverse catchments in Australia – one wet tropical catchment in Queensland and one temperate ephemeral catchment in Western Australia. There are however strengths and weaknesses to each approach and there exists some debate within the literature as to which approach is likely to provide the most accurate predictions of large-scale hydrological phenomena (Beven 1989; Grayson, Moore & McMahon 1992; Koster & Milly 1997; Schulz & Beven 2003; Zhang et al. 2004).

Since the choice of a specific model parameterisation will obviously influence the simulation results and thus our assessment of the utility of GRACE in improving such simulations, our framework calls for at least two separate models of the MDB using the two distinct approaches. The lumped conceptual approach has been implemented using the SIMHYD rainfall-runoff model code (Chiew, Peel & Western 2002). The current version of this model discretises the MDB into 26 major catchments with meteorological forcing (precipitation and potential evapotranspiration) from 87 Bureau of Meteorology weather stations used to drive the model on a daily time step. The model was calibrated using an automated pattern search optimization routine to find the best fit between simulated runoff and available stream gauge records maintained by the various State Agencies within the MDB. Because stream flow in major river catchments of the MDB is typically affected by a complex system of storages and diversions that are not easily accounted for, a non-calibrated version of this model is also being developed which uses regionalised parameters based on the analysis of calibrations from smaller unimpaired catchments (Peel et al. 2000).

The physically-based parameterisation proposed for this work is the NASA Catchment Land Surface Model – CLSM (Koster et al. 2000). CLSM is a state-of-the-art LSM which uses physically-based equations to calculate the flux of water and energy through the system, including an explicit representation of the variability of soil moisture within the catchment and its impact on evapotranspiration and runoff generation. This model breaks with tradition of LSM developments in that it defines the hydrological catchment as the fundamental computational unit rather than an arbitrary grid cell. As a result the model is able to account for the effects of topography on multi-dimensional flow processes and thus remove the bias towards one-dimensional vertical physics that is inherent in other LSMs.

Since the implementation of CLSM to the MDB is still under development, the results presented in this paper are for the conceptual SIMHYD-based model only. Work is also being carried out with models that have already been developed over the MDB region including the LSM implemented in the Australian Bureau of Meteorology's LAPS operational weather forecasting model (Viterbo & Beljaars 1995). Recent results from this work have demonstrated the potential for GRACE to help identify unrealistic model behaviour in the simulation of soil moisture which could ultimately lead to improvements in the Bureau's weather forecasts (Ellett et al. 2005).

4.2 Data assimilation

Hydrological model predictions are inevitably uncertain as a result of errors in model structure, parameters, initial conditions and input forcing data. The purpose of data assimilation (DA) is to improve the prediction of hydrological state variables by integrating independent observations with the model estimates in a statistically optimal fashion. Although DA has been used for many years in atmospheric and oceanic science to improve model prediction, it is only in the last few years that research has really begun to focus on incorporating DA methods into hydrological modelling (Walker, Houser & Reichle 2003). Much of this new research has centred on the assimilation of remotely sensed observations of near surface soil moisture (Houser et al. 1998; Walker, Wilgoose & Kalma 2001).

Recent studies have also demonstrated the effectiveness of DA in improving the prediction of soil moisture in the CLSM model specifically proposed in this framework (Walker & Houser 2001; Reichle et al. 2002). However, the potential benefit of using DA methods with GRACE observations has thus far only been investigated in the preliminary synthetic study of Ellett et al. (2004) and is therefore a major objective of this research.

In the context of GRACE observations, DA methods can be used to provide a means of improving the catchment-scale water storage state estimates (e.g. soil moisture and ground water) from the monthly-mean basin-scale total water storage observation provided by GRACE. In the simplest case the monthly change in total water storage observed by GRACE may be considered error free and thus the exact difference between GRACE observations and the model prediction of total storage change (i.e. the sum of all catchment-scale storages) can be used to correct the forecast model states by the method known as direct insertion. This method can be expressed mathematically as

$$\mathbf{X}^a = \mathbf{X}^b + \mathbf{K}(\mathbf{Z} - \mathbf{Z}') \quad (5)$$

where $\mathbf{X}^a$ is the analysis vector of updated catchment-scale water storage state predictions, $\mathbf{X}^b$ is the background vector of initial model estimates of water storage states, **K** is the gain matrix (equal to 1 in this case), **Z** is the total storage change observation from GRACE and **Z′** is the initial model estimate of total basin storage change. **Z′** is calculated as the matrix product of **H** with $\mathbf{X}^b$ where **H** is a transformation matrix which effectively upscales the model state vector (e.g. individual catchment-scale soil moisture and ground water storages) to the observation state space corresponding to **Z** (i.e. the single basin-scale total water storage from GRACE).

One of the limitations of the direct insertion approach, however, is that GRACE observations will not be entirely error free and are likely to have an associated uncertainty of 4-15 mm (Rodell & Famiglietti 1999; Wahr et al. 2004). Moreover, the uncertainty in model predictions of water storages is variable over time and space and finding the optimal state estimates requires the appropriate weighting being placed on the model predictions relative to the observations from GRACE. A further complication to using direct insertion and other direct observer methods (e.g. Kalman Filter) for GRACE DA lies in the very coarse temporal and spatial resolution of the observation relative to other observations that have already been shown to be useful in hydrological DA/modelling systems (Walker & Houser 2005). More specifically, even at the resolution of the observation (i.e. the basin scale), GRACE provides a quantity that is integrated through time (i.e. monthly mean total storage) rather than a "snapshot" of the state of the system at a discrete time.

An alternative approach that is perhaps more suited to GRACE DA is the variational method. The variational method is in essence an optimisation problem in which the optimal estimate of initial model states is found by minimising an objective function penalising the difference between the model and observations over a prescribed window of time (Walker & Houser 2005). For example, with GRACE this time window could be set as 1 month. This leads to the minimisation problem in which a single GRACE observation of total basin-wide, monthly-mean storage is then compared to the model's estimate of the same quantity (found at the end of the month by integrating all catchment-scale storages over the time window) to determine the optimal estimate of what the initial state of the system must have been at the beginning of the month in order to match the observation by GRACE (given the appropriate consideration of error in both GRACE and the model).

In addition to handling the integrated time scale of GRACE, the variational method is also capable of spatially downscaling observations without the need for *a priori* methods (Reichle, Entekhabi & McLaughlin 2001). This is clearly advantageous since some approach to downscaling is a necessary component to using GRACE for improving estimation at the catchment scale. Indeed, early findings from the synthetic study of Ellett et al. (2004) have indicated that variational DA of GRACE observations can improve model prediction of soil moisture states at not only the basin scale, but also the catchment scale due to this effective downscaling capability.

4.3 Ground-based monitoring

A network of ground-based monitoring stations has been installed throughout the Murrumbidgee Catchment in order to evaluate model performance and the effectiveness of GRACE DA in improving model prediction at the catchment scale. Data from the network are also combined with additional measurements of ground water, surface water and snow cover throughout the basin to provide an estimate of the MDB total water storage signal. In the present study this estimate serves as a measure for assessing the likelihood that GRACE will provide a useful observation for analysis in the MDB. Ultimately we intend to use scaling methods along with additional data in order to provide an observation-based validation of GRACE. Such a validation is clearly important but presently lacking. Early studies on GRACE have thus far relied on model outputs for evaluation of GRACE observations (Rodell et al. 2004; Tapley et al. 2004b; Wahr et al. 2004).

The Murrumbidgee Catchment was selected for field validation based on its representativeness of the larger MDB and the ability to capitalise on existing instrumentation. Earlier work involving evaluation of the Bureau's LSM led to the establishment of 18 soil moisture monitoring sites being installed across the catchment in September 2001 (Western et al. 2002). Throughout late 2003 and early 2004, 20 new sites were installed in two focused study areas of the catchment—the Kyeamba Creek sub-catchment and the Yanco/Coleambally area. Another study involving local scale salinity processes added 8 more sites within the Kyeamba Creek sub-catchment bringing the total number of monitoring sites in the network to 46.

Figure 1 shows the location of the monitoring sites distributed throughout the Murrumbidgee catchment (note that individual sites in the two focused study areas are not shown due to the scale). Also in Figure 1 is the distribution of average annual precipitation throughout the MDB which shows that the basin-wide variability in annual average precipitation is quite similar to the variability observed within the Murrumbidgee catchment.

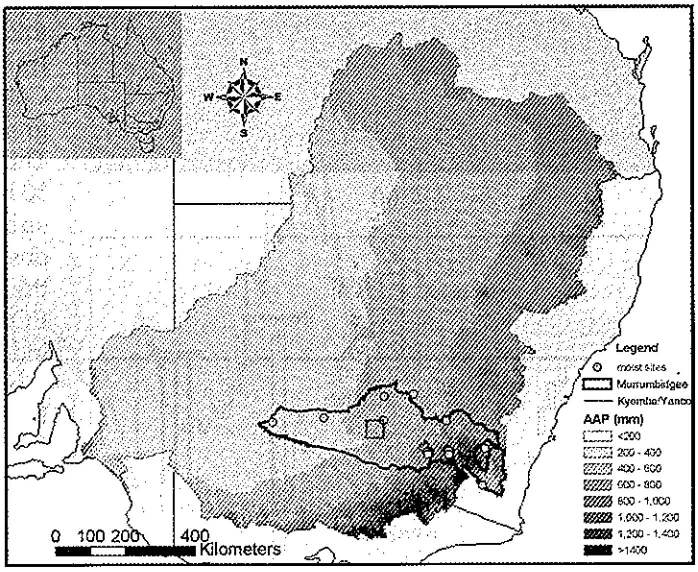
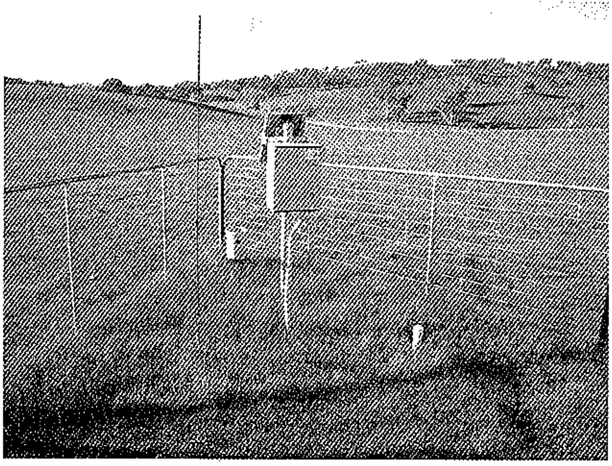


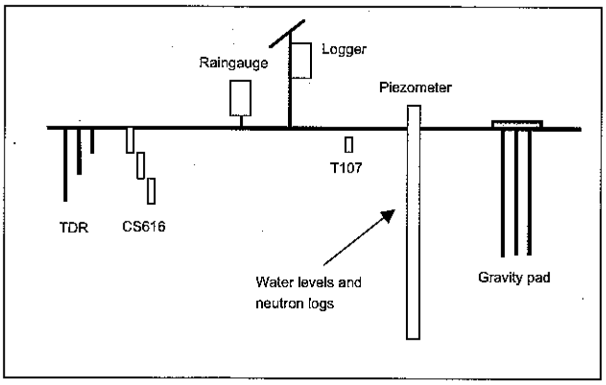
Figure 1: The distribution of average annual precipitation throughout the Murray-Darling Basin and the location of the Murrumbidgee Catchment monitoring network (bold outline) and the Kyeamba and Yanco focused study areas (light outline)

Similar representativeness was found for other variables such as potential evapotranspiration, soil types and topographic distribution which suggests that the catchment mean response measured by the Murrumbidgee network (~ 10^5 km^2) will be highly correlated to the signal measured by GRACE over the MDB (~ 10^6 km^2). All monitoring sites use automated data logging devices to collect continuous measurements on a 20-minute interval.

Figure 2a shows a typical site in the Kyeamba sub-catchment area with moderate topographic relief, perennial grass vegetation type and grazing land use. Much of the instrumentation is below ground and is shown schematically in figure 2b. Water storage measurements include: (1) root-zone soil moisture (RZSM) at 0-30, 30-60 and 60-90 cm depth from water content reflectometers (Campbell Scientific Inc. model CS615 and CS616), (2) RZSM from Time Domain Reflectometry (periodic measurements using the Soilmoisture Equipment Corp. TRASE system to aid in the calibration of the water content reflectometers), (3) deeper vadose zone soil moisture from neutron moisture meter logging (also a periodic measurement made ~ seasonally using a CPN model 503DR Hydroprobe) and (4) ground water table fluctuation from capacitance probes installed in piezometers (Odyssey probe from Dataflow Systems Pty Ltd.). Other measurements include rainfall from tipping bucket rain gauges (Campbell Scientific Inc. model TB4) and soil temperature at 10 cm depth from thermistors (Campbell Scientific model T-107). The companion study of Smith et al. (2005) also describes the use of a portable field-based gravity meter for taking periodic gravity measurements at the sites.



(a)



(b)

Figure 2: Monitoring site in the Kyeamba Creek sub-catchment and schematic diagram of instrumentation

The overall sampling scheme of the 46 sites in the network is to provide representative measurements of the factors that are likely to exhibit a dominant control on the variability in terrestrial water storage (e.g. climate, land use, topography, soil type and vegetation cover). In the Kyeamba Creek sub-catchment focused study area a nested design allows us to examine the scaling behaviour of water storage in the transition from the farm scale (~1 km^2) to the Murrumbidgee Catchment scale (~10^5 km^2) by way of 4 increasingly larger scales of observation. The sites are distributed across 14 distinct locations within the sub-catchment (area ~ 600 km^2) ranging from steep slopes in the upper reaches of the catchment to flat valley fill sites near its mouth. The dominant land uses in this area are grazing and dryland cropping with some undisturbed areas in the upper slopes of the catchment. The geology is characterised by granitoids in the upper parts of the catchment and deformed metasediments throughout the lower areas.

The Yanco/Coleambally focused study area lies in the broad western plains of the MDB where the topography is flat with very few geological outcroppings. Soil types are predominantly duplex sandy loams and are less variable than in the eastern highlands. The 13 sites are evenly divided between the 3 main land uses in the region—irrigated cropping (including the major rice growing region of the Coleambally Irrigation Area) dryland cropping and grazing (typically perennial grass type vegetation). The sites were located in a grid-based design over a 50 km x 50 km area allowing for measurement of the sub-grid variability of other remote-sensed observations such as near-surface soil moisture from the Advanced Microwave Scanning Radiometer for EOS (http://sharaku.eorc.nasda.go.jp/AMSR/index_e. htm). Additional detail on the Murrumbidgee monitoring network can be found on the HYDROGRACE project website at: http://www.oznet.unimelb. edu.au.

5 EARLY RESULTS FROM GROUND-BASED MEASUREMENTS

Although measurements from the complete Murrumbidgee network are still subject to validation, data from the 18 original installations spanning the entire catchment area provide insight on the magnitude and dynamics of changes in the soil moisture component of water storage. Figure 3 shows the time series of RZSM from 5 sites located within the Kyeamba Creek catchment along with the mean profiles for both the Kyeamba and Murrumbidgee catchments. These measurements show how the range in variability in RZSM is reduced when averaging over larger spatial extents of the Kyeamba Creek and Murrumbidgee catchments.

A key aspect of these results is the fact that although none of the five individual sites exhibit the exact response observed in the Kyeamba or Murrumbidgee mean catchment profiles, all of the sites are consistently above or below the mean time series (for example the Ginninderra 1 and 2 sites are generally always 30-40 mm greater than the Kyeamba mean value and 20-30 mm greater than the Murrumbidgee mean value). This supports the CASMM concept (Catchment Average Soil Moisture Monitoring) introduced by Grayson and Western (1998) which suggests that there exist certain points within a catchment that are representative of the overall mean catchment behaviour and thus provide representative measurements of the areal mean values. The importance of these results to our study lies in the

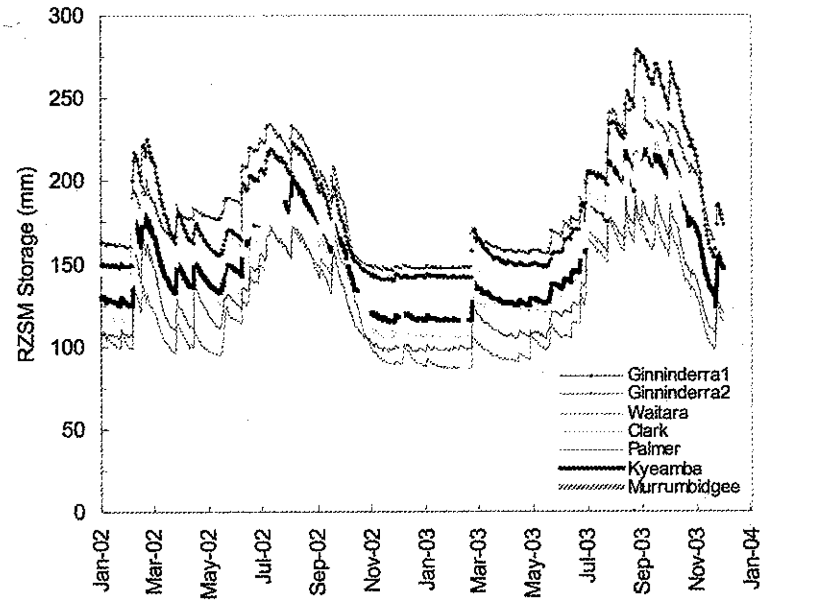


Figure 3: Time series of root-zone soil moisture storage in the Kyeamba Creek sub-catchment and the mean profile of the Murrumbidgee catchment

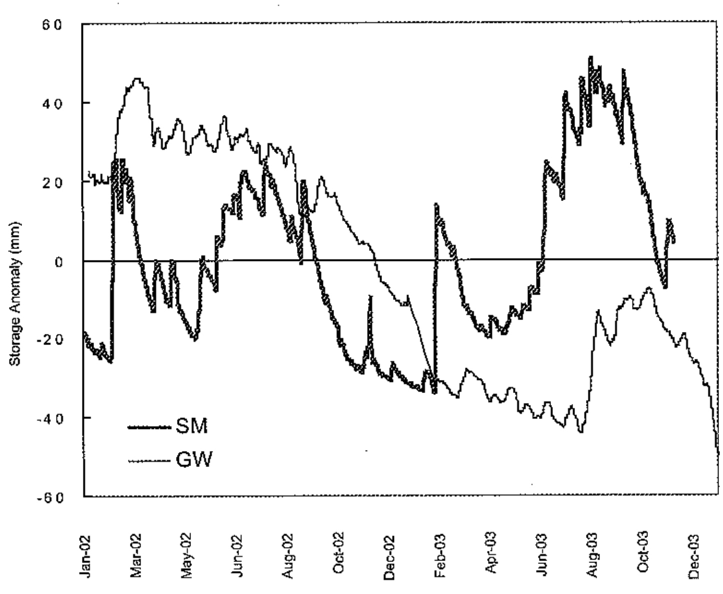


Figure 4: Variations in soil moisture versus ground water

increased likelihood that a reasonable scheme for scaling between GRACE and ground-based observations can successfully be developed.

Measurements of ground water level variation from 2002-2003 are available from the Kyeamba Creek sub-catchment (figure 4). Water level variations were converted to storage changes by using an estimated specific yield value of 0.1 which is an average value for the predominantly silty clay type soils (Maidment 1993). Also shown in figure 4 is the Murrumbidgee catchment mean soil moisture profile and both series are reported as anomalies from their mean values over the 2-year period.

Comparing the 2 series in figure 4 illustrates the dynamic nature of soil moisture variability relative to ground water storage. Large, rapid changes observed in soil moisture such as the ~ 40 mm infiltration in February 2003 are naturally dampened in the ground water system. On a monthly mean basis the soil moisture changes account for ~ 75% of the total storage variability. However, soil moisture exhibits strong seasonality owing to the seasonality in evaporative forcing (rainfall is fairly uniformly distributed throughout the year in the Murrumbidgee and much of the MDB) and thus on an inter-annual timescale the storage changes are dominated by ground water variability. For the period 2002-2003 the magnitude of ground water storage change was more than 6 times greater than the change in RZSM (-52 mm versus + 8 mm respectively). This suggests that GRACE may prove to be a useful tool for tracking the ground water status of the basin on an inter-annual basis.

In order for GRACE to provide a useful measure of storage change on a monthly basis the magnitude of the natural variability across the MDB must exceed the inherent error in GRACE. An estimate of the basin-wide monthly mean total storage change signal is shown in figure 5. The estimate was obtained by combining the Murrumbidgee measurements with additional data on the major MDB surface water storages provided by the New South Wales Department of Infrastructure, Planning and Natural

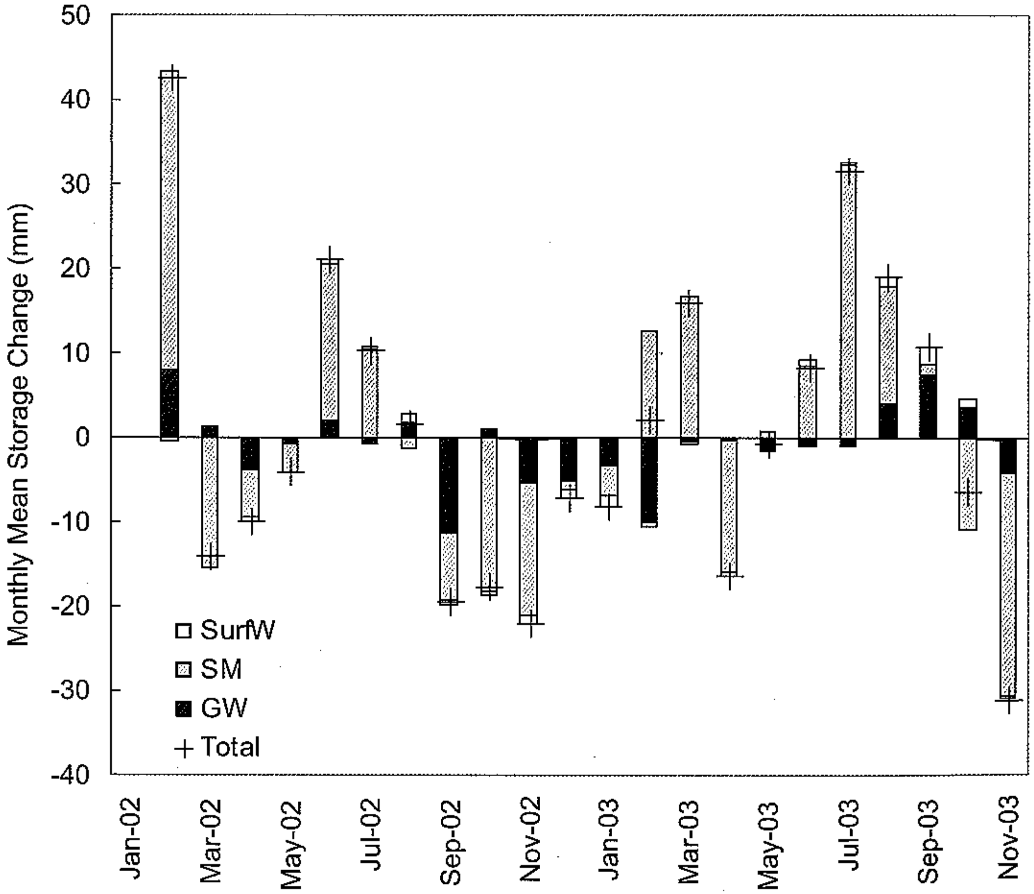


Figure 5: Estimate of the monthly mean change in total water storage for the Murray-Darling Basin

Resources. Snow data was obtained from Snowy Hydro Limited but proved to be negligible in terms of a basin-wide storage component.

The Murrumbidgee network mean soil moisture measurement was assumed to be representative of the larger MDB, while the Kyeamba ground water signal was reduced by one–half in light of a recent basin-wide ground water study which indicates that this area is more variable than the overall basin (Ife and Skelt 2004).

The results in figure 5 confirm that GRACE is likely to yield a statistically significant measure of water storage change throughout the MDB. Monthly storage changes over this time period average 15 mm with a maximum of +43 mm from January to February 2002. The magnitude of the changes exceed the ~ 15 mm upper bound of uncertainty estimated by Wahr et al. (2004) 50% of the time, and the 4 mm pre-launch estimate 86% of the time. These results are clearly encouraging with respect to the potential for GRACE to provide useful new data on the hydrology of the MDB, and to help assess model performance and contribute in a DA framework.

6 EARLY RESULTS FROM MODELLING

Results from the SIMHYD model for the Murrumbidgee catchment are presented in Figure 6. Comparing the simulated and measured soil moisture storages shows that the model generally performs in a satisfactory manner but that it consistently over predicts the magnitude of changes in soil moisture storage that result from the infiltration of rainfall (increases or positive changes) and evapotranspiration (decreases or negative changes). The model simulated range in annual amplitude of soil moisture storage change was 66% greater than the measured change in 2002 (93 versus 56 mm, respectively) and 20% greater than measured in 2003 (102 versus 85 mm). Since hydrological processes are intimately linked through the water balance, the model errors in storage change ultimately translate into errors in the prediction of evapotranspiration, runoff and ground water recharge fluxes.

This dependency is illustrated further in Figure 7 which compares the model simulated runoff against the stream gauge measurements at Balranald near the outflow point of the catchment. The calculated runoff from the model (simulated daily and summed to provide a monthly total) never exceeds 4 mm per

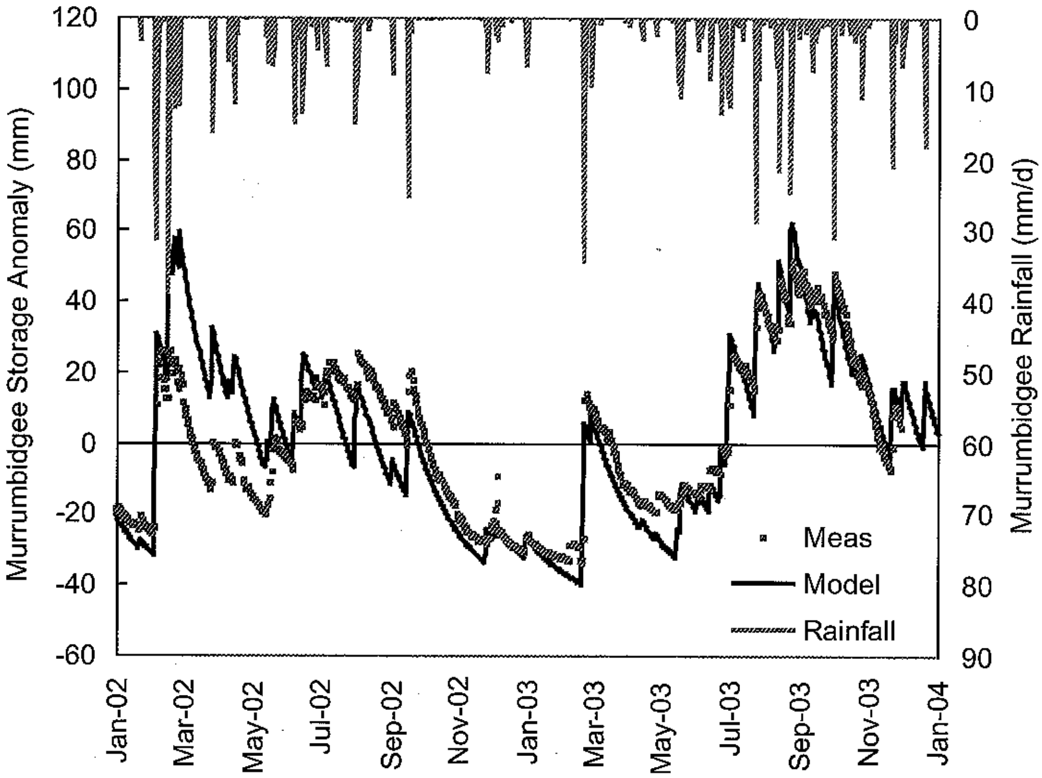


Figure 6: Comparison of measured and model simulated soil moisture storage in the Murrumbidgee catchment

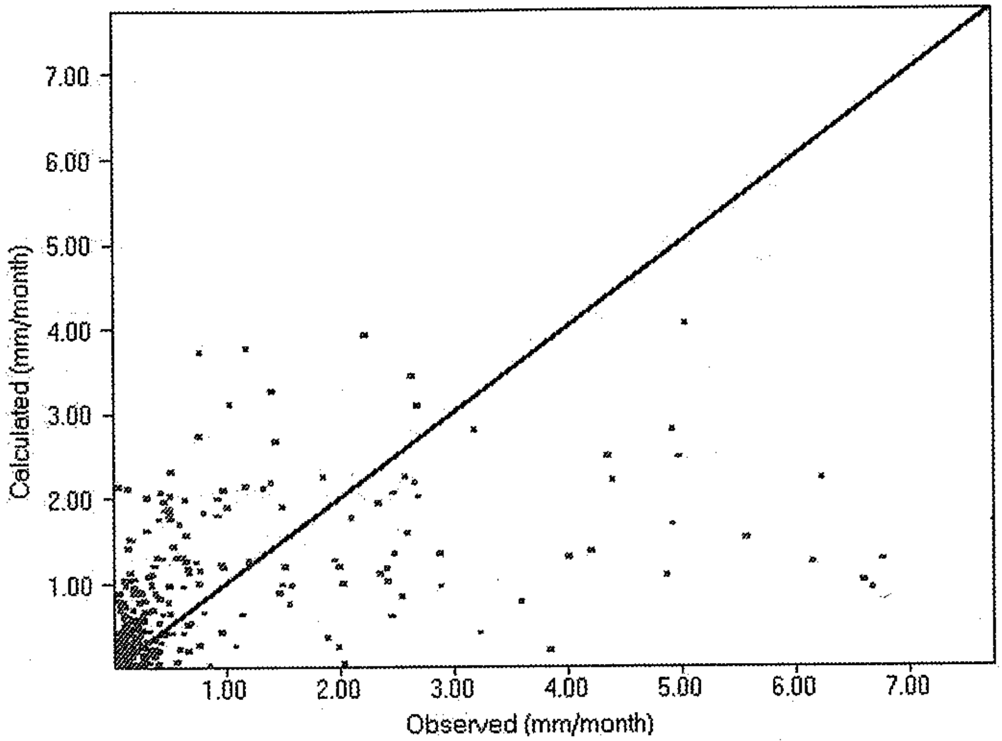


Figure 7: Model calculated versus observed runoff in the Murrumbidgee catchment

month whereas the observed stream flow measurements show that monthly volumes can often reach a value that is about twice as large as the model predictions. It should be noted, however, that some of this error can also be attributed to anthropogenic effects of storage releases and diversions which are not explicitly accounted for in the model at present.

7 CONCLUSIONS

This study presents a framework for assessing the utility of GRACE satellite observations in providing new insight on the hydrology of the Murray-Darling Basin. The framework combines hydrological modelling and data assimilation techniques with ground-based monitoring in order to investigate ways in which GRACE may help to improve understanding of the integrated hydrological system. Early results from ground-based measurements indicate that GRACE should provide a statistically significant measure of basin-wide storage change at the monthly time scale, thus allowing a unique assessment of the seasonal and inter-annual evolution of water storage across the MDB. Such novel observations should also lead to new estimates of evapotranspiration flux and possibly a means of assessing the effectiveness of recent revegetation efforts in reducing ground water recharge throughout the basin.

The results from this study also indicate the potential for GRACE to provide a fundamentally new contribution in the quest to improve hydrological models of the MDB region. In particular, GRACE should provide an important new measure for assessing the uncertainty in model prediction of water storage and evapotranspiration flux. GRACE may also aid in model development by shedding light on the relative strengths and weaknesses of various parameterisation approaches for large-scale hydrological models. Work is already underway to further investigate this application of GRACE in the MDB (Ellett et al. 2005). Finally, the results from this study, along with the preliminary synthetic work of Ellett et al. (2004) illustrate the potential for GRACE to directly improve large-scale hydrological model prediction through the use of DA methods. Given that water resources management in the MDB is increasingly underpinned by such models, GRACE shows great potential in making important practical contributions to this matter of national importance.

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