

Gravimetry And Its Application To Geohydrology :

A review

Gaathier Mahed

Department of Geology and Soil Science, Unit for Environmental Sciences and Management,
North-West University, Private bag X6001, Potchefstroom, 2520, South Africa,
gaathier.mahed@gmail.com

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Abstract

The application of gravity to Geohydrology is reviewed. A short background and history related to the application of geophysics to Geohydrology is outlined. Multiple works related to ground based gravimetry applied to the hydrological sciences in general are examined. These include the possible errors which might occur when applying gravimetry to hydrological studies. Furthermore, the satellite based applications of gravity for hydrology are also briefly outlined in order to compare to the aforementioned ground based gravity. Then a review of the most recent works related to hydrological modelling and correlation with residual gravity signals is shown in order to highlight the usefulness of this geophysical tool. International as well as African case studies are mentioned in order to highlight applicability. Thereafter a South African context of studies related to gravity is shown with a focus on the South African Geodynamic Observatory at Sutherland. Lastly the future outlook of gravity studies is examined in order to advance work in this arena and guide studies to come.

1. Introduction

Water quantity and supply are of major concern in many parts of the world. With an ever increasing population and a constant water supply, it will be difficult to provide clean potable water for everybody (Miller, 2002). It is therefore of the utmost importance that current resources are managed properly and new groundwater resources are explored.

Cook (2003) has listed applicable tools for maximising groundwater exploration and aquifer characterisation in fractured rock aquifers. Understanding these secondary fractured saturated units is becoming increasingly important as they underlie a large part of South Africa (Woodford and Chevallier, 2002). Sami and Murray (1998) have shown that these aquifers, with the right management, can aid in the water supply of rural areas. Xu and Beekman (2003) highlight the problems relating to managing groundwater in Southern Africa by examining methods for recharge estimation, as well as many local case studies.

Kirsch (2006) has highlighted the many geophysical tools applicable to groundwater studies. It has been shown that resistivity, magnetic surveys and gravimetry all aid in aquifer characterisation

and groundwater exploration. Milsom (2003) shows that resistivity as a method can be applied successfully to groundwater exploration with resistivity of water being directly proportional to its quality, due to the lack of conducting ions. This means that the quality of the groundwater could also be inferred from resistivity studies. Magnetic surveys on the other hand are used in fractured rock environments, such as the Karoo, to target dykes, which may act as flow barriers for groundwater (Woodford and Chevallier, 2002).

These previously mentioned tools, were initially extensively used in mineral exploration as shown by Kearey and Brooks (1991). With the recent advancements in technology and a greater understanding of the subsurface we find that the same tools are now being used in groundwater exploration (Kirsch, 2006). With regards to gravimetry and its applicability to groundwater, Kearey and Brooks (1991) mention the fact that local aquifer geometry could be inferred from mobile gravimetry measurements. Duque et al. (2008) further state that gravity should be used in conjunction with other tools, such as time domain electromagnetic soundings and stratigraphy, in order to improve its efficacy as a tool to delineate aquifer boundaries.

The combination of the aforementioned methods has also lead to the need for more robust tools for understanding subsurface fluid flow. It has recently been shown that the use of gravity data could shed a substantial amount of light on geohydrology at the basin as well as field scale, as shown by Chen et al. (2016) and Christiansen et al. (2011), respectively.

2. Ground based gravimetry applied to hydrology:

The presence and occurrence of moisture in the vicinity of gravimeters has long been suspected to create background noise during gravity measurements (Heiskanen and Vening Meinesz, 1958). This led to early applications of ground based gravimetry for groundwater exploration purposes. Wallace and Spangler (1970), for example, applied a gravimetric and seismic survey in order to characterise the extent of a hydrogeological basin in an arid area of southwest U.S.A. Bulk densities of subsurface material as well as porosity values were utilised in conjunction with the geophysical parameters to determine the storage capacity of the basin. This study proved that the coupling of non-intrusive geophysical methods is excellent for inferring specific hydrogeological parameters on a groundwater basin scale (Wallace and Spangler, 1970).

Llubes et al. (2004) compared three studies in the region of major SG (Superconducting Gravimetre) stations across the European continent. An important differentiation was made with regards to classification of groundwater flow systems relative to their proximity to the SG stations, namely regional and continental flow (Llubes et al., 2004). Furthermore, the importance of environmental data as well as an understanding of the geology and groundwater is critical for interpretation of SG data, as re-emphasized by Jacob et al. (2008). In this respect assumptions that neglect vertical flow on a local scale in soil must be re-examined, as this has shown to be critical in soil moisture movement (Fetter, 1999).

Harnisch and Harnisch (2006) examined seven SG stations throughout the world and the gravity and hydrological data stemming from these facilities. They concluded that great spatial and temporal variation occurs at every single site. This was attributed to the variable climatic conditions and thus in turn hydrological regime. Furthermore, the underlying geology also plays a critical role in determining soil type and characteristics (Fey, 2010). In line with understanding subsurface fluid flow, Kroner and Jahr (2005) showed that hydrologic variations in the subsurface can greatly aid in geohydrological modelling. Experiments in the vicinity of the SG at Moxa, Germany, for example, showed that anthropogenically induced interflow caused a marked difference in the gravity field and in turn allowed quantification of subsurface moisture differences.

Naujoks et al. (2007) also examined the hydrological variations in the vicinity of the superconducting gravimeter in Moxa, Germany, using mobile gravimetres. 17 monitoring campaigns were completed between November 2004 to April 2007, using 9 Lacoste and Romberg relative gravimeters. The small-scale study area, in the immediate vicinity of the SG, meant that the precision of the measurements was less than 1 microgal. The most important conclusion drawn is the fact that a greater understanding of the geohydrology is needed in order to fully appreciate the application of gravimetric data to hydrological studies. Naujoks et al. (2007) have shown that the standard deviations, in the vicinity of the Moxa SG station, could be as much as 14nm/s^2 for a specific point. The spatial variation on the other hand was much greater and standard deviations measured up to 171nm/s^2 .

A dolomitic aquifer, in the south of France, formed the focus of a gravity study by Jacob et al. (2008). A simple conservation of mass energy could be applied to this scenario to ascertain inputs by precipitation and outputs as spring flow (Xu and Beekman, 2003). Three absolute gravimeters with rainfall stations at each location were utilised for data generation (Jacob et al., 2008). Gravity variation is considered to be a major factor for soil moisture at the local scale, and it was concluded, verifying observations by Cook (2003), that multiple parameter modelling is important for removing uncertainty with regards to variables affecting groundwater flow. The frequency of gravity measurements, as also shown by Naujoks et al. (2007), aids in capturing the seasonal hydrological signal and thus the variation in subsurface moisture storage. This in turn aids with correlation of the gravity signal to the hydrological modelling. Jacob et al. (2008) have shown that gravity is an excellent tool for determining mass movement of fluids in the subsurface.

Wziontek et al. (2009) examined the relationship between the distance from the SG and the cumulative gravity effect. They concluded that site specific studies are critical for understanding local hydrological effects and their relationship to gravity residuals. Boy and Hinderer (2006) validated this work, and emphasise further that greater understanding of every single aspect of the water balance and its relationship to the SG was needed in order to correctly quantify and remove the hydrological signal of the SG. A study of soil profiles, surface water, ground water, as well as mobile gravimetry highlighted the spatial and temporal variation within the vicinity of the SG at

Moxa and emphasises the complex task of hydrological modelling in order to understand the gravimetric signal (Krause et al., 2009).

Whilst it can clearly be seen that the applications for gravity in the field of hydrology have great potential, problematic issues arise around scale, calibration and correlation with numerical modelling. Furthermore, a good understanding of the geology and soils of the area is also critical, as previously mentioned. All of these issues are highlighted in the above listed studies. It can also be seen how the knowledge related to the relationship between hydrology and gravity has evolved over the past few years. Initially it was thought that only variations in groundwater levels could be detected (e.g Howle et al., 2003), but soil moisture as well as the spatial and temporal variations in gravity are now also being observed. This is due to the increased understanding of gravity applications in hydrology (Christiansen et al., 2011) and the increase in precision of instruments like the SG (Kennedy et al., 2014).

With all this said, one also has to take cognisance of the possible errors that can arise and how they might be mitigated. Christiansen et al. (2011) have compiled many of the possible errors, the estimated amplitude for error, as well as mitigation measures which could be taken in order to reduce error. All of these were extracted from literature, including personal experience. These possible errors should be noted when attempting to complete any gravity survey as well as in the interpretation of the data in order to not adversely affect the results. Some of these errors include, but are not limited to :

- Unexplained background drift
- Calibration errors
- Ocean loading effects
- Spring hysteresis

The work of Duque et al. (2008) has shown that the application of gravity, in conjunction with time domain electromagnetic soundings, was useful in determining the freshwater interface in a aquifer in the south of Spain. This study also highlights the fact that multiple tools are required in order to properly calibrate the results stemming from gravity. Duque et al. (2008) also applied geological mapping, well logging as well as groundwater geochemistry in order to properly delineate the aquifer and the freshwater interface.

3. Satellite based gravity applications related to geohydrology

In the past the tedious task of hydrologic and hydrogeological monitoring was done only via insitu point sources, and from which the data was then extrapolated over larger areas, by means for example of kriging (Schultz and Engman, 2000). The use of satellite applications has greatly stimulated the evolution of more rapid monitoring in recent times. Furthermore, Meijerink (2007) produced an all encompassing practical manual on remote sensing applications for hydrogeology.

Neumeyer et al. (2006(a)) compared Gravity Recovery and Climate Experiment (GRACE) and SG data from the major SG stations, which form part of the GGP. (Global Geodynamics Programme) The WaterGAP Global Hydrological Model (WGHM) and the Land Dynamics Model (LaD) (Table 1), were then correlated to the GRACE and SG data at each station. The Leaky Bucket model, also known as the H96 model, was also utilized in the previous study. Despite a few outliers at specific stations, there seems to be a general agreement between the GRACE, SG and hydrological model time series for the various SG stations. Correlation values as high as 0.75 and 0.72 were calculated between the SG and H96 as well as the GRACE and H96, respectively. Major differences in the models lie in the method used to calculate snow cover and the depth to groundwater (Neumeyer et al., 2006(a)). Boy and Hinderer (2006) drew similar conclusions when comparing the GLDAS (Global Land Data Assimilation System) and LaD (Land Dynamics) global hydrological models to the hydrological gravity residual of 20 SG stations all over the world. Suggestions were made that groundwater measurements, soil moisture as well as precipitation measurement instrumentation should be installed at all the stations in order to better understand the local hydrological effect on the SG readings (Neumeyer et al., 2006(a)). This has shown to increase the understanding of the hydrological regime and thus in turn better model it and correlate to the gravity residual.

Table 1 : Comparison of global hydrological models used in major Satellite gravimetry studies

| Model Name | Meaning of Abbreviation | Developer | Spatial Resolution (cell grid size) | Temporal Resolution | Global Distribution maps |
|-------------------|--------------------------------------|--------------------------|--|---------------------------------|--|
| WGHM | WaterGAP Global Hydrological Model | Döll et al., (2003) | 0.5°x0.5° | 24 hours (one day) | Soil (FAO, 1995) Drainage (Döll and Lerner, 2002) |
| LaD | Land Dynamics Model | Milly and Shmakin (2002) | 1°x1° | Minutes to an hour | Soil (Zobler, 1986) Vegetation (Matthews, 1983) |
| GLDAS | Global Land Data Assimilation System | Rodell et al. (2004) | 0.25°; 0.5° ;1.0°; 2.0°x2.5° | Adjustable time step and output | Soil (Reynolds et al. 1999) ; Vegetation (Hansen et al. 2000) |

Werth and Güntner (2010) utilised GRACE data in order to calibrate a global hydrological model for 28 of the world's major river basins (Figure 1). The major aim of the study was to calibrate the WGHM model with GRACE data and the groundwater, surface water, soil moisture and precipitation were the major model inputs. The study showed that hydrogeologic data was sorely lacking in hydrology models. Furthermore, model calibration is critical, specifically under certain climatic conditions due to the role of hydrological parameters being highly variable in differing environmental circumstances (Werth and Güntner, 2010). The GRACE data added value to the calibration of most of the basins, but further work is needed in order to validate the individual water storage components.

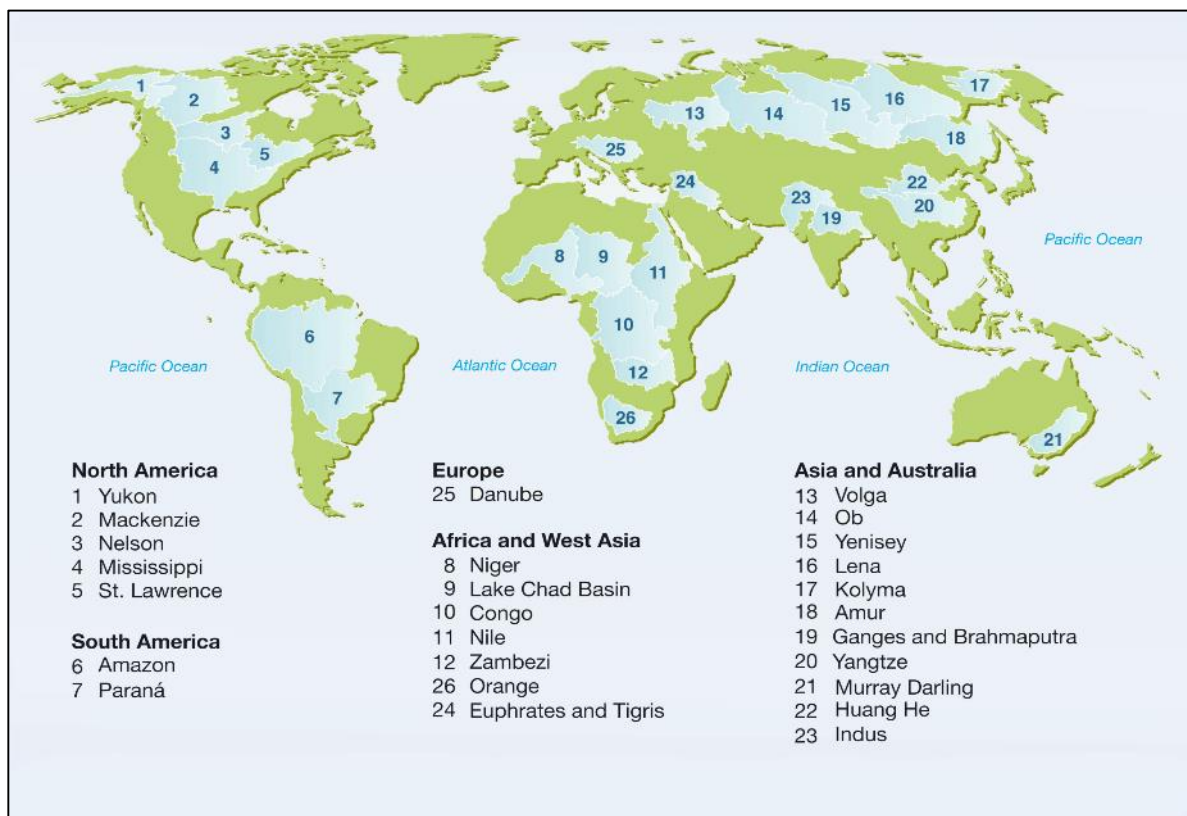


Figure 1. The 28 of the World's major River basins used by Werth and Güntner (2010) in their study used to calibrate the WGHM. The Tigris and Euphrates, as well as Ganges and Brahmaputra, have been grouped into single basins. (UNEP, 2008)

Hinderer et al. (2009) argue that GRACE estimates for changes in terrestrial water storage are not comparable to ground based SG measurements. It has been argued therefore that the choice of hydrological model, model calibration and scale play a major role in determining the value of the results (Leavesley et al., 2002). More recently this has been re-examined by Krause et al. (2009), who concluded that the soil moisture model results correlated well with the gravity residual for the SG at Moxa, for a small catchment of approximately 2km². 77% of the variability stemming from the SG residual could be explained by changes in soil moisture. Niu et al. (2007) further illustrate that simple large scale hydrogeological modelling has had greater success with GRACE correlations. Neumeyer et al. (2006(a)) have shown up to 75% correlation between large scale models and GRACE.

Fukuda et al. (2009) also compared GRACE and hydrological modelling. They raised the point that a groundwater component should be included in the hydrological modelling due to the increase in groundwater storage and therefore gravity variability. It was also emphasized again that GRACE is more applicable on a regional scale (Werth and Güntner, 2010). Total Water Storage (TWS) from Global hydrological models were compared to GRACE measurements and it can be clearly seen that the differences between the two methods is small. Thus, the resolution between the various hydrological modelling methods is steadily improving. This is especially true for larger hydrological basins with a definite seasonal pattern in terms of hydrology (Chen et al., 2016).

When comparing multiple studies using ground and satellite based gravity to hydrological models, it seems as if the SG stations in areas of relatively stable seasonal weather conditions have a stronger correlation to the GRACE signal than those in areas of erratic changes in climate. Examples of these are included in the studies of Harnisch and Harnisch (2006) as well as by Neumeyer et al. (2006(a)). This also depends on the hydrological model used, model inputs and calibration methods..

In East Africa Becker et al. (2010) studied the water balance in the great lakes using GRACE, satellite altimetry and precipitation data. Lakes Victoria, Tanganyika, Malawi and Turkana were examined by Becker et al. (2010), whilst the last large lake was excluded from a similar study undertaken by Swenson and Wahr (2009). Another major difference is the fact that Swenson and Wahr (2009) utilised LEGOS as well as ICESat for altimetry, instead of Envisat, Jason 1 and Poseidon, which was used by Becker et al. (2010) for the same purpose. Furthermore, Becker et al. (2010) used the WaterGAP global hydrological model in order to better understand the variation in the levels of the lakes in the area. Swenson and Wahr (2009) on the other hand applied a water balance equation and included the calculation of evaporation from the lake surface. Both studies conclude that GRACE, in conjunction with other satellite tools, is useful for calibrating remotely sensed water storage.

Güntner (2009) tabulated most of the major work related to GRACE and hydrology prior to 2006. Therefore these works were omitted and the reader is referred to this comprehensive study. The most pertinent factors to consider when using GRACE to calibrate hydrological studies were compiled in the aforementioned work and include :

- Consistency of water storage components
- Error estimates for GRACE data
- Consistency of the water balance multi-criterial evaluation
- Signal separation
- Multi model comparison
- Longer time scales

These suggestions were noted and the study of Jiangcun et al. (2009) compares multiple large scale hydrological models alongside GRACE data in the immediate vicinity of SG stations globally. The work of Neumeyer et al. (2006(a)) was completed in a similar fashion, except that the authors included multiple GRACE solutions from more than one processing centre. This comparison ,between the results from various processing centres, was also undertaken by Mahed (2012) with comparable results between processing centres at the Sutherland station (Figure 2).

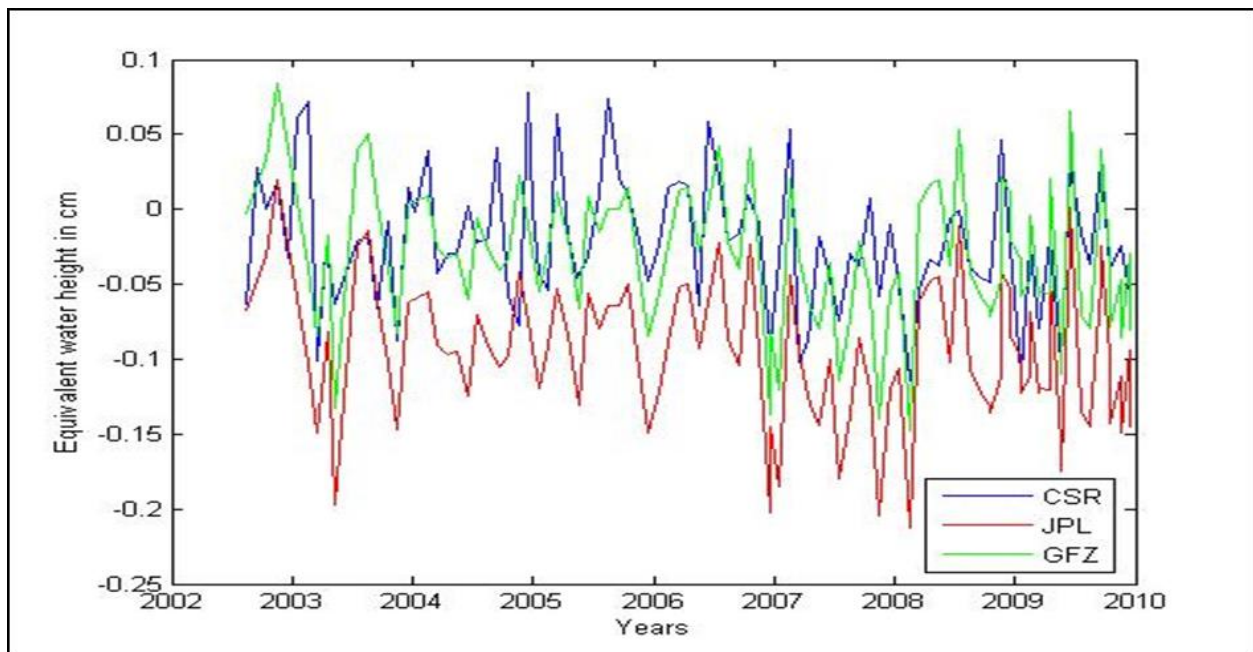


Figure 2. The results of GRACE data for the Sutherland site, processed by the various research centres. The Jet Propulsion Laboratory (JPL), GeoforschungsZentrum (GFZ) and the Centre for Space Research (CSR) all have their own solutions for the data stemming from the satellite with minor variations occurring. (Mahed et al., 2010)

4. A South African perspective

The use of the SG at South African Geodynamic Observatory, Sutherland (SAGOS) is important for the quantification of changes in water storage, which directly impact local economies, particularly in the semi-arid Karoo. Work has recently been undertaken by using the SG to understand subsurface water flow and storage in the semi-arid Karoo (Mahed, 2012). This is the location for SAGOS, typical of a large percentage of the South African landscape in terms of geology, climate and hydrology.

The installation of 4 groundwater wells was undertaken (Mahed, 2016). This is besides the one shallow well, which probably monitors interflow, used by Harnsich and Harnsich (2006). Furthermore, soil moisture sensors were also installed in the immediate vicinity of the SG at varying depths. Another weather station was also installed in close proximity to the soil moisture sensors in order to understand the impacts of weather and climate on the Vadose zone (Mahed, 2012).

Harnisch and Harnisch (2006) were the first to examine the data from the SG at Sutherland (Figure 3). The correlation coefficient between the change in groundwater level at well SA BK 07 and the gravity residual, which can be seen as the processed signal with a remaining TWS signal, was computed and shown to be -0.22. This indicates an inverse relationship between gravity and the water level in this particular well, with a minor relationship. It should however be noted that initial works in the field of gravity applied to hydrology seem to assume that correlation equals causation. This is problematic and needs further investigation. No corrections were made to the groundwater

data due to the limited amount of available data, when compared to the gravity residual data. Furthermore, the gravity residual, which can be seen as the processed signal with a remaining TWS signal, and the modelled gravity effect of precipitation only had a weak correlation coefficient of 0.041.



Figure 3. The location of the Sutherland site as well as the layout of the groundwater wells, indicated with SA BK prior to the well number. The site also has an A pan to measure evaporation and the SG located on a hill.

5. Future outlook

The SG station at Sutherland has one SG installed and another SG in storage, which was initially meant for an SG station in South America. It is proposed that the inactive SG be installed at the newly built geodetic station at Maatjiesfontein. The ground based SG will complement the space geodetic instruments proposed for installation at the site (Combrinck et al., 2007). In this manner the measurements of two SG's could be directly compared to one another. The effect of local hydrology at various locations could be compared at a higher resolution and in both cases in fractured rock environments. Another possibility is the use of a new mobile SG in conjunction with Lacoste and Romberg gravimeters at various locations across the entire catchment. This has been done by Naujoks et al. (2007) at Moxa and highlighted the variability in gravity residual spatially as well as temporally.

Hinderer et al (2009) call for a better understanding of the hydrological regime on a small scale in order to better examine the impact which hydrology has on the SG. This is important in order to remove the residual hydrological signal from the SG. This is even more important at Sutherland due

to the erratic nature of the rainfall, as well as high evapotranspiration. This in turn adversely affects runoff, recharge and soil moisture which means the variability in water storage is also erratic. This variability is ultimately what impacts the SG residual signal and needs to be fully understood in order to have a SG signal free of any “noise”.

It is important to calibrate GRACE with other satellite tools, such as Soil Moisture Ocean Salinity (SMOS) and MODIS, in order to aid in precision and calibration of large scale hydrological models (Werth and Güntner, 2010). This inclusion of multiple tools will definitely aid in precision and could thus be used in order to compare to local scale models and the SG in particular. Furthermore, more work is required in order to better understand and calibrate the groundwater aspects of TWS.

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7. References

- Becker, M, Llovel, W, Cazenave, A, Güntner, A. and Crétaux, JF, 2010, Recent Hydrological behaviour of the East African great Lakes region inferred from GRACE, satellite altimetry and rainfall observations, *Comptes Rendes Geoscience*, vol. 342, no. 3, pp. 223-233.
- Boy, J and Hinderer, J, 2006, ‘Study of the seasonal gravity signal in superconducting gravimeter data’, *Geodynamics*, vol. 41, Issue 1-3, pp. 227-233.
- Christiansen, L, Haarder, EB, Hansen, AB, Looms, MC, Binning, PJ, Rosbjerg, D, Andersen, OB and Bauer-Gottwein, P, 2011, ‘Calibrating Vadose Zone Models with Time-Lapse Gravity Data’, *Vadose Zone*, vol. 10, no. 3, pp.1034-1044.
- Cook, P, 2003, *A guide to regional groundwater flow in fractured rock aquifers*, Seaview Publishers, South Australia
- Chen, JL, Wilson, CR, Tapley, BD, Scanlon, B and Günter, A, 2016, Long-term groundwater storage change in Victoria, Australia from satellite gravity and in-situ observations, *Global and Planetary change*, vol. 139, pp. 56-65.
- Döll, P & Lerner, B, 2002, ‘Validation of a new 30-min drainage direction map’, *Hydrology*, Volume: 258, no. 1-4, pp. 214-231
- Döll, P, Kaspar, F, and Lehner, B, 2003, ‘A global hydrological model for deriving water availability indicators: model tuning and validation’, *Hydrology*, vol. 270, no 1-2, pp.105-134.
- Duque, C, Calvache, ML, Pedrera, A, Martin-Rosales, W and Lopez-Chicano, M, 2008, Combined Time Domain electromagnetic soundings and gravimetry to determine marine intrusion in a detrital coastal aquifer (Southern Spain), *Hydrology*, vol. 349, no. 3-4, pp. 536-547.
- FAO (1995), FAO (Food and Agriculture Organization), 1995. Digital Soil Map of the World and Derived Soil Properties, CD-ROM Version 3.5, FAO, Rome.
- Fetter, CW, 1999, *Contaminant Hydrogeology*, 2nd Edition, Prentice Hall Inc, Upper Saddle River, New Jersey.
- Fey, M, 2010, *Soils of South Africa*, Cambridge University Press, Cape Town

Fukuda, Y, Yamamoto, K, Hasegawa, T, Nakaegawa, T, Nishijima, J and Taniguchi, J, 2009, 'Monitoring Groundwater variation by satellite and implications for in-situ gravity measurements', *Science of the Total Environment*, vol. 407, no. 8, p 3173-3180.

Güntner, A, 2009, 'Improvement of Global hydrological models using GRACE', *Surveys of Geophysics*, vol. 29, no. 4-5, pp. 375-397.

Hansen, MC, Defries, RS, Townsend, JRG and Sohlberg, R, 2000, Global land cover classification at 1km spatial resolution using a classification tree approach, *International Journal of Remote Sensing*, vol. 21, no. 6-7, pp. 1331-1364.

Harnisch, G and Harnisch, M, 2006, 'Hydrological influences in long gravimetric data series', *Geodynamics*, vol. 41, no.1-3, pp. 276-287.

Heiskanen, WA and Vening-Meinesz, FA, 1958, *The Earth and its gravity field*, Mc-Graw Hill, New York

Hinderer, J, De Linage, C, Boy, JP, Gegout, P, Masson, F, Rogister, Y, Amalvict, M, Pfeffer, J, Little, F, Luck, B, Bayer, R, Champollion, C, Collard, P, Le Moigne, N, Diament, M, Deroussic, S, de Viron, O, Biancale, R, Lemoine, JM, Bonvalot, S, Gabalda, G, Bock, O, Genthong, P, Boucher, M, Favreau, G, Séguis, L, Delclaux, F, Cappelaere, B, Oi, M, Descloitres, M, Galle, S, Laurent, JP, Legchenko, A, and Bouin, MN, 2009, 'The GHYRAF (Gravity and Hydrology in Africa) experiment: Description and first results', *Geodynamics*, vol. 48, no. 1-3 pp. 172-181.

Huang, J., Van Den Dool, H.M. and Georgarakos, K.P., 1996, 'Analysis of Model-Calculated Soil Moisture over the United States (1931-1993) and applications to Long-Range Temperature Forecasts', *Climate*, vol. 9, no. 6, pp.1350-1362.

Jacob, T, Bayer, R, Chery, J, Jourde, H, Le Moigne, N, Boy, JP, Hinderer, J, Luck, B and Brunet, P, 2008, 'Absolute gravity monitoring of water storage variation in a Karst aquifer on the Larzac plateau (Southern France)', *Hydrology*, vol. 359, no. 1-2, pp. 105-117.

JiangCun, Z, HePing, S, and JianQiao, Xu, 2009, 'Validating Global hydrological models by ground and space gravimetry', *Chinese Science Bulletin*, vol. 54, no. 9, pp. 1534-1542.

Kearey, P and Brooks, M, 1991, *An Introduction to geophysical exploration (2nd Edition)*, Blackwell, Oxford

Kennedy, J., Ferre, T.P.A., Günter, A., Abe, M. and Creutzfeldt, B, 2014, Direct measurement of subsurface mass change using the variable baseline gravity gradient method, *Geophysical Research Letters*, vol. 41, no. 8, pp. 2827-2834

Kerr, Y, Waldteufel, P, Wigneron, JP, Martanuzzi, J, Font, J, 2001, 'Soil moisture retrieval from space : the Soil Moisture and Ocean Salinity (SMOS) mission', *IEEE transactions on Geoscience and Remote Sensing*, vol. 39, no. 8, pp. 1729-1735.

Kirsch, R, 2006, *Groundwater Geophysics: A tool for hydrogeology*, Springer-Verlag, Berlin.

Krause, P, Naujoks, M, Fink, K. and Kroner, C. 2009, 'The impact of soil moisture changes on gravity residuals obtained with a superconducting gravimeter', *Hydrology*, vol. 373, no. 1-2, pp.151-163.

Kroner, C and Jahr, T, 2005, 'Hydrological experiments around the superconducting gravimeter at Moxa Observatory', *Geodynamics*, vol 41, no. 1-3, pp. 268-275.

Leavesley, GH, Markstrom, SL, Restrepo, PJ and Viger, RJ, 2002, 'A modular approach to addressing model design, scale and parameter issues in distributed hydrological modelling', *Hydrological processes*, vol. 16, no. 2, pp. 173-187.

Llubes, M, Florsch, N, Hinderer, J, Longuevergne, L and Amalvict, M, 2004, 'Local Hydrology, the Global Geodynamics project and CHAMP/GRACE perspective: some case studies', *Geodynamics*, Vol. 38, no. 3-5, pp. 355-374.

Mahed, G, De Wit, M, Decoure, M, Gunter, M, Kreutzfeld, B and Kroner C 2010, 'Analysis of temporal and spatial variation in water storage for the area of South African Geodynamic Observatory, Sutherland South Africa' European Geophysical Union, Vienna, May 2010, p. 15718, Copernicus, Vienna, May 2010.

Mahed, G. (2012), Analysis of temporal and spatial variation in water storage by means of gravimetric and hydrologic methods in the region around the South African Gravimetric Observation Station, PhD thesis, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa.

Mahed, G, 2016, Development of a conceptual geohydrological model for a fractured rock aquifer in the Karoo, near Sutherland, South Africa, *South African Journal of Geology*, vol. 119, no. 1, pp. 33-38.

Matthews, E, 1983, 'Global Vegetation and Land Use: New High-Resolution Data Bases for Climate Studies', *Climate and Applied Meteorology*, vol. 22, no. 3, pp. 474-487.

Miller, GT, 2002, *Living in the Environment*, 12th Edition, Brooks Cole, Belmont, California

Milly, P and Shmakin, A, 2002, 'Global modelling of land, water and energy balances. Part 1 : The land dynamics (LaD) model', *Hydrometeorology*, vol. 3, no. 3, pp. 283-299.

Milsom, J, 2003, *Field Geophysics*, 3rd Edition, Wiley Publishers, West Sussex, United Kingdom.

Naujoks, M, Weise, A, Kroner, C, and Jahr, T, 2007, 'Detection of small hydrological Variations in gravity by repeated observations with relative gravimeters', *Geodesy*, vol. 82, no. 9, p. 543-553.

Neumeyer, J, Barthelmes, F, Dierks O, Flechtner, F, Harnisch, M, Harnisch, G, Hinderer, J, Imanishi, Y, Kroner, C, Meurers, B, Petrovic, S, Reigber, C, Schmidt, R, Schwintzer, P, Sun, HP and Virtanen, H, 2006a, 'Combination of temporal gravity variations resulting from superconducting gravimeter (SG) recordings, GRACE satellite observations and global hydrology models', *Geodesy*, vol. 79, no. 10-11, pp. 573-585.

Neumeyer J, Barthelmes F, Dierks O, Hartmut, P and Fourie, P, 2006b, 'High Precision gravity measurements with the dual sphere superconducting gravimeter in Sutherland', *South African Journal of Geology*, vol. 109, no. 4, pp. 515-520.

Niu, GY, Yang, ZL, Dickinson, RE, Gulden, LE and Su, H, 2007, 'Development of a simple groundwater model for use in climate models and evaluation with Gravity Recovery and Climate experiment data', *Geophysical Research*, vol. 112, no. 7, pp. 1-14.

Rodell, M, Houser, PR, Jambor, U, Gottschalk, J, Mitchell, K, Meng, CJ, Arsenault, K, Cosgrove, B, Radakovich, J, Bosilovich, M, Entin, JK, Walker, JP, Lohmann, D, and Toll, D, 2004, 'The Global Land Data Assimilation System', *Bulletin of the American Meteorological Society*, vol. 85, no. 3, pp. 381-394.

Sami, K and Murray, EC, 1998, *Guidelines for the evaluation of water resources for rural development with an emphasis on groundwater*, Water Research Commission, Pretoria

Schultz, GA and Engman, ET, 2000, *Remote sensing in hydrology and water management*, Springer-Verlag, Berlin.

Swenson, S and Wahr, J, 2009, 'Monitoring the water balance of Lake Victoria, East Africa, from space', *Hydrology*, vol. 370, no. 1-4, pp. 163-176

UNEP, 2008, *Vital Water Graphics – An overview of the World's Fresh and Marine Waters*, 2nd edition, UNEP, Nairobi, Kenya.

Wallace, DE and Spangler, DP, 1970, 'Estimating storage capacity in deep alluvium by gravity-seismic methods', *Bulletin of International Association of Science and Hydrology*, vol. 5, no. 2, pp. 91-104.

Werth, S and Güntner, A, 2010, 'Calibration analysis for water storage variability of the global hydrological model WGHM', *Hydrology and Earth Systems Science Discussions*, vol. 14, no. 1 pp. 59-78

Woodford, AC and Chevallier, L, 2002, *Hydrogeology of the main Karoo Basin-Current Knowledge and future research needs*, Water Research Commission, Pretoria

Wziontek, H, Wilmes, H, Wolf, P, Werth, S and Günter, A, 2009, 'Time series of superconducting gravimeters and water storage variations from the global hydrology WGHM', *Geodynamics*, vol. 48, no. 3-5 pp. 166-171.

Xu, Y and Beekman, HE, 2003, Groundwater Recharge Estimation in Southern Africa, UNESCO, Paris

Zobler, L, 1986, 'A world soil file for global climate modeling', National Aeronautics and Space Administration, Tech Memo no. 87802.