Emerging Science and Technology for Deep Groundwater Resource Assessment

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Abstract

A thick, extensive fractured-rock (FR) aquifer system like the Table Mountain Group (TMG) in South Africa, provides unique opportunity for fundamental advances in understanding interactions between fluid flow and mechanical deformation, through analysis of the "hydromechanical" coupling in FR permeability, fluid transport and deep storage in fracture porosity. For the ~1 km thick Peninsula Aquifer in the TMG, present knowledge of skeletal-framework compressibility, the main unknown used in calculating specific storage, is based on published data from similar rocks elsewhere. The South African Water Research Commission recently obtained laboratory measurements of elastic properties of TMG borehole-core samples, but up-scaling from dry-sample measurements at ~10-cm scale to saturated rock volumes on 100- to 1000-m scale, is methodologically problematic.

These problems are obviated by measuring directly the compaction of, and corresponding surface subsidence above, the pumped aquifer and using these field-experimental measurements to determine the framework compressibility and the specific storage. Historically, such aquifer-deformation measurements have used costly devices (borehole extensometers), but recent advances in GNSS technology (e.g., GPS), and also Interferometric Synthetic Aperture Radar (InSAR), now provide noninvasive methods of geospatial data collection, which can be used in conjunction with borehole hydrograph information to estimate the specific storage and hydraulic conductivity of the aquifers.

This African project contributes to an international effort to develop the Global Geodetic Observation System (GGOS) towards a global-to-regional-scale monitoring of the full hydrological cycle. It supports capacity-building in space-geodetic data-processing, modelling of the hydrological cycle, and interpretation of observations in terms of terrestrial water storage.

Introduction

Water is the essence of life and crucial to human welfare, progress and sustainable development. The global hydrological cycle operates on a continuum of spatial and temporal scales, and is transformed continuously by climate change, erosion, pollution, agriculture, and civil engineering practices. Despite its fundamental role for mankind, the importance of its variability in regulating flood, drought, and disease hazards, the challenges posed by increasingly limited availability of water for human activities, knowledge of key quantities of the hydrological cycle is associated with large degrees of uncertainty, and urgent questions still defy answer.

Since the inception of sustained interest in the large-scale fractured-rock aquifers in the Table Mountain Group (TMG) (Figure 1), e.g., the Deep Artesian Groundwater for Oudtshoorn Municipal Supply (DAGEOS) Project in 1999-2000 (Umvoto Africa, 2005), a quiet scientific revolution has occurred and is gathering momentum in respect of the application of modern Earth Observation (EO) and space-geodetic methods. New technologies for groundwater monitoring and resource assessment are now emerging, with implications for the exploration, development and management of the hidden resources within deep artesian basins that are characteristic of the TMG aquifer systems.

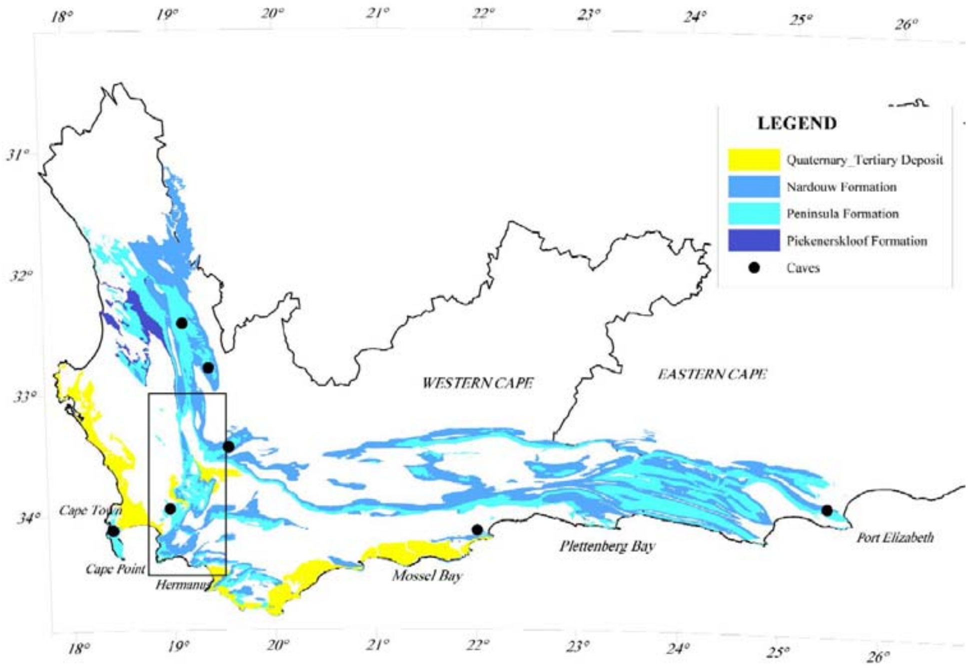

Figure 1 Distribution of the Table Mountain Group (TMG), with the Peninsula Aquifer shown in light blue

Following the Johannesburg World Conference on Sustainable Development (WSSD) in 2002, the Group on Earth Observation (GEO) aims to establish a Global Earth Observation System of Systems (GEOSS) by 2015, through a 10-year implementation plan. "Water" is among the 9 focus topics in the GEOSS Implementation. Its priority requirements are flood forecasting and an integrated (satellite-based, ground-calibrated) global monitoring system for droughts, but groundwater assessment also figures prominently.

A recent Water Research Commission (WRC) report on the DAGEOS Project (Umvoto Africa, 2005, Chapter 5) outlines a design strategy for the monitoring of changes in continental water storage (surface and subsurface) and the remote-sensing of the hydromechanical structure and properties of the deep confined fractured-rock aquifer systems of the Western Cape province by land- and space-based systems, with particular reference to the application of new EO technologies. Its focus is an experimental system using a combination of land-based microgravity and Global Positioning System (GPS) observations, complemented by satellite gravity and satellite radar methods for (i) monitoring deep-aquifer storage changes and (ii) determining fundamental hydromechanical properties of the aquifer such as its bulk compressibility.

To use Global Navigational Satellite Systems (GNSS) such as GPS to constrain large-scale water storage changes in the TMG aquifers through the Western Cape province, and to make use of GPS measurements to recover the elastic properties of the deeper confined aquifers at particular sites, requires an extensive array of permanent, continuously-recording GPS stations. The Chief Directorate: Surveys and Mapping (CDSM) within the South African Department of Land Affairs operates a nationwide "TrigNet" array of such beacons, often co-located with South African Weather Service stations. Apart from tracking crustal movements to millimeter-per-year precision, and thus contribute to understanding of plate tectonics, strain/stress patterns, and earthquake hazard in the subcontinent (Calais et al., 2006; Hartnady et al, 2007), TrigNet provides a convenient platform for developing a new space- and groundbased system for monitoring the seasonal or abstraction-induced fluctuations in aquifer storage through detection of associated, small surface deformations.

The recent development by the Overstrand Municipality of the Gateway Wellfield, near Hermanus in the Western Cape province, and its proximity to the TrigNet station HERM in the grounds of the Hermanus Magnetic Observatory (Figure 2), provides a unique opportunity to link its groundwater-monitoring systems to a local surface deformation-monitoring experiment, in the context of a long-term (~1 year), large-scale abstraction test.

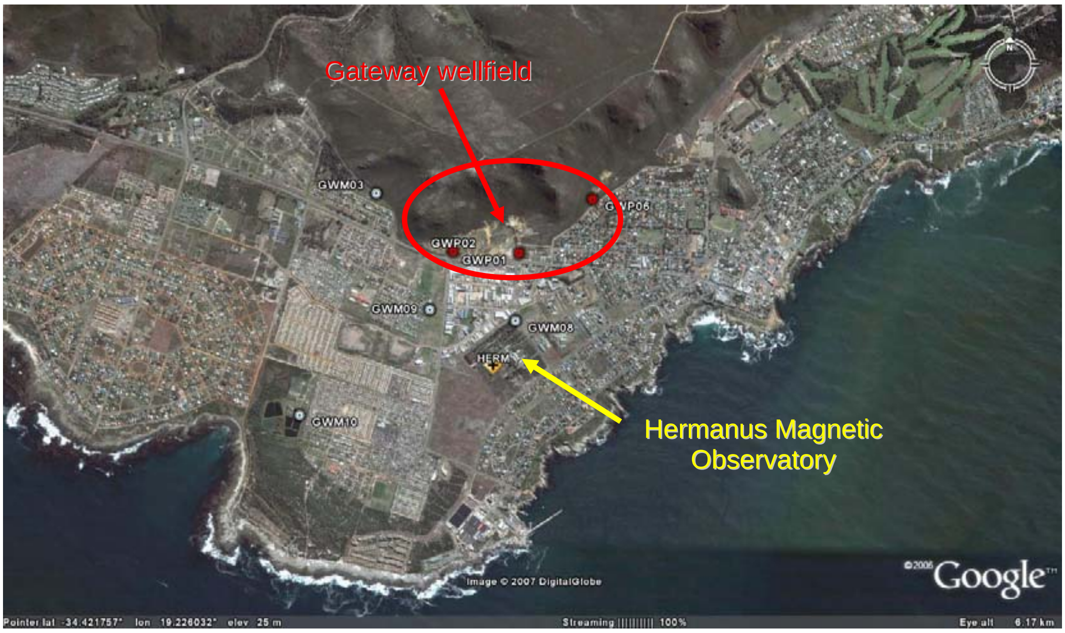

Figure 2 Hermanus Gateway wellfield and Trignet station HERM at Hermanus Magnetic Observatory

From this local experiment, it is anticipated that an innovative methodology will emerge for regional-space-based monitoring and continuous assessment of deep groundwater resources, adding to the conventional methods of water resource monitoring, envisaged in the provisions of Chapter 14 of the National Water Act.

Project Aims

The WRC has accepted the proposal for a three-year (2008-2011) project on "Development and Application of Global Navigational Satellite Systems (GNSS) Methodology for Groundwater Resource Assessment", with the following three aims:

1. To demonstrate the use of high-precision GNSS technology as a tool for groundwater resource monitoring and assessment;
2. To develop the methodology for relating GNSS measurements of natural or abstraction-induced surface deformation and conjunctive hydrogeological data in order to derive the in-situ, bulk elastic properties (e.g., skeletal compressibility) of an underlying confined fractured-rock aquifer;
3. To build South African capacity to establish the technical infrastructure (e.g., data telemetry) and implement the data-processing methods required for a pilot GNSS-for-Groundwater scheme at the Gateway Wellfield, Hermanus

Methodology

A fractured-rock aquifer system as thick and extensive as the TMG in the Western Cape provides a unique opportunity to make fundamental advances in understanding the effects of interaction between the flow of fluid and the mechanical deformation within the aquifers, through rigorous process-analysis of the "hydromechanical" (HM) coupling (Stephansson, 2003) involved in fractured-rock permeability, fluid transport and deep storage in fracture porosity. Provided appropriate action is taken to obtain quantitative measurements of key HM variables during the course of the extended test-pumping regime, the Gateway test-pumping experiment can contribute greatly to that opportunity.

At present our knowledge of the skeletal-framework compressibility for the Peninsula Aquifer, which is the main unknown quantity used in the calculation of its specific storage, is based only on published data from similar rock types elsewhere in the world. The WRC recently commissioned laboratory measurements of the elastic properties of TMG borehole-core samples (Du Preez et al., 2006), but extrapolation or up-scaling from these measurements, on dry samples at ~10-cm scale, to saturated rock volumes on 100- to 1000-m scale, is methodologically problematic.

Recent field and analytical studies also demonstrate that horizontal movements induced by pumping from a confined aquifer can be of the same order of magnitude as vertical compaction (Burbey and Helm, 1999). When horizontal strain is induced, vertical compaction for a specified stress distribution is greatly reduced, and approximately two-thirds of the total volume strain originates from horizontal compaction. The actual specific storage in an isotropic aquifer may therefore be double that calculated when only vertical strain is assumed (Burbey, 1999).

To obviate these problems it is technically preferable to measure directly the compaction of, and corresponding surface subsidence above, the pumped aquifer and to use these field-experimental measurements to determine the framework compressibility and the specific storage. Historically, such aquifer-deformation measurements have used costly devices (borehole extensometers), but recent advances in GNSS technology (e.g., GPS), and also Interferometric Synthetic Aperture Radar (InSAR), now provide noninvasive methods of data collection, which can be used in conjunction with borehole hydrograph information to estimate the specific storage and hydraulic conductivity of the compressible units (Burbey, 2001).

The TrigNet station HERM (Figure 3), operated by the Chief Directorate: Surveys and Mapping (CDSM) is well placed to serve as a baseline geodetic datum for an experiment to

measure the induced deformation of the Peninsula Aquifer, during the early stages of a long-term test-pumping experiment that is provisionally scheduled to commence in 2008.
The measurement procedure will take advantage of the changed operation of HERM from its original 14-hr continuously recording (1 Hz frequency) basis to a full 24-hr continuous operational mode.

Figure 3 Trignet station HERM, at Hermanus Magnetic Observatory (HMO), stationed close to a weather station.

The use of GPS instruments and signal-recording support for the aquifer-deformation measurements are secured through scientific and technical collaboration with the Directorate: Survey Services in CDSM (R.T. Wonnacott). Data processing and interpretation support is secured through scientific collaboration with the Department of Earth and Atmospheric Sciences (E. Calais) in Purdue University, USA, and follows a routine procedure established for tectonic plate-motion studies (Calais et al., 2006; Hartnady, 2002; Hartnady et al., 2007).

TrigNet Data Processing

Data from continuous TRIGNET sites is processed along with data from all International GNSS Service (IGS) stations currently operating throughout the region of Africa and the Indian Ocean. Using the GAMIT software version 10.2 (King and Bock 2005), the procedure solves for station coordinates, satellite state vectors, one tropospheric delay every four hours at each site, horizontal tropospheric gradients, and phase ambiguities using double-differenced GPS phase measurements, with IGS final orbits and IERS earth orientation parameters relaxed. Elevation-dependent antenna phase-centre models are applied following the tables recommended by the IGS, as are solid-Earth, polar-tide, and ocean-loading corrections following the IERS standards (IERS, 1996).

Position-time series are then calculated for each site, from which are estimated process noise parameters (white and random walk noise). The TrigNet daily solutions are combined with global solutions from the IGS daily processing, routinely performed at Scripps Institution of

Oceanography, while applying site-dependent random-walk noise, and a loosely constrained combined solution is obtained. Minimizing the position and velocity deviations of 38 globally distributed IGS core stations with respect to the International Terrestrial Reference Frame 2000 (ITRF2000; Altamimi et al. 2002) while estimating an orientation and translation transformation, imposes the reference frame.

Finally the angular velocity of the Nubia (NU) plate relative to ITRF2000 is estimated using 3 IGS stations (MAS1, NKLG, GOUG) on the wider Nubian plate, 3 IGS stations in the south-western part of South Africa (Sutherland-SUTH, SUTM, Simon’s Town-SIMO), and 6 TrigNet stations in the same region (Mowbray-MBRY, Langebaan-LGBN, Springbok-SBOK, Calvinia-CALV, De Aar-DEAR, Port Elizabeth-PELB). Local velocities computed from this NUITRF200 rotation are subtracted from the ITRF2000 velocities to obtain residual velocities with respect to this particular definition of NU. Results for these NU stations, based on daily data from January 2000 to June 2007, have already been presented (Hartnady et al., 2007).

Similar results from the TrigNet station HERM will be obtained by processing archive data for the interval between its conversion to a 24-hr continuous basis and the start of the Gateway long-term test-pumping experiment. Prior to the start of this experiment, a few satellite GNSS instruments will be established at benchmarks within and around the Gateway Wellfield to detect the rate and direction of ground-surface motions induced by fluid abstraction from the confined Peninsula Aquifer. HERM itself is located about 700 m south of the aquifer compartment beneath the Gateway Wellfield, across a major ENE-WSW-striking normal fault zone (Hermanus Fault), which is considered to form an impermeable barrier to groundwater movement (Figure 4).

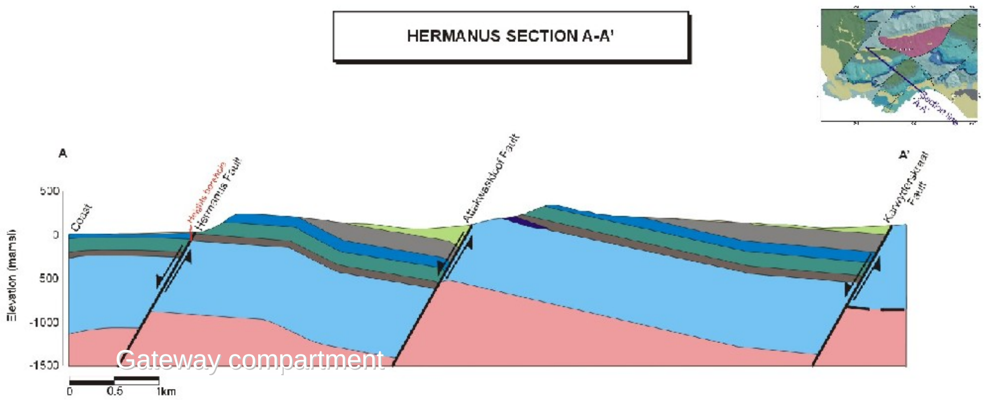

Figure 4 **Confined Peninsula Aquifer and Gateway compartment**

The induced deformations are therefore not expected to extend to HERM, but it will nevertheless be treated as part of the Gateway array in order to test this assumption.

GNSS Interpretation Methods

The GNSS results will be periodically compared with the results of potentiometric surface (aquifer pressure) measurements at the pumped and monitoring boreholes within and around the wellfield, and with the predictions of 3-D finite-element numerical (FEFLOW) modeling of aquifer behaviour. From these comparisons, it is expected that in-situ estimates of fundamental hydromechanical parameters (e.g., bulk framework compressibility, Poisson's ratio, specific storage) will be extracted.

Over the three-year period of this study, which contains two full hydrological years (October 2008 to September 2010), an investigation of the seasonal variation in the vertical time series of the HERM reference site, together with a Gateway GPS station least affected by the test-pumping experiment, is also expected to yield useful information about aquifer properties and annual recharge potential. In focusing on the groundwater as a possible cause of any observed displacements, model-simulated strains caused by pore-water pressure changes are assumed responsible for the vertical coordinate changes, as has been demonstrated in Japan. At the IGS site TSKB (Tsukuba) the vertical displacements measured in a nearby 190 m-deep well by a subsidence meter (borehole extensometer), which measures displacements that occur at depth shallower than well bottom, were compared with the GPS series. An elastic -deformation model successfully explains 65% of the variances of the GPS time series, and finds that water tables between 40 m and 190 m are responsible for the displacements. The volume compressibility of the rocks in that interval is estimated at ~3×10^{-9} m^2/N (Munekane et al., 2003).

ITRF2000 velocity components in the north, east and vertical directions are already well known for the IGS station SUTH at South African Astronomical Observatory (SAAO) in Sutherland (cf. http://sopac.ucsd.edu/cgibin/refinedTimeSeriesListing.cgi). Over a ~9-year interval (1998.29-2007.46) the SUTH vertical time-series shows an apparent secular uplift in the ITRF2000 frame of 3.4 ± 0.9 mm/yr, on which is superimposed a clear annual fluctuation with a peak-to peak amplitude of several (~5-10) millimeters. In this annual cycle of the SUTH vertical component, the peak occurs shortly after the start of each year, during the summer season, and the trough coincides with the cold winter season.

Relating the seasonal uplift-subsidence signal to near-field water storage changes around SUTH is possible from the environmental data record (borehole water level and rainfall). The collocated South African Geodynamic Observatory at Sutherland (SAGOS) maintains continuous monitoring of water levels in a borehole ~2 km distant from the vault of the TT70 Superconducting Gravimeter (SG), and keeps meteorological records of rainfall and barometric pressure. These environmental data are used to correct the SG record for the transient effects of atmospheric pressure and water storage fluctuations in nearby shallow aquifers. Between August 2001 and June 2002, the SAGOS groundwater-level and precipitation records (J. Neumeyer, personal communication, 2002) show a water-level fall by ~30 cm, from a peak in September to a trough in February-March, presumably due to evapotranspiration from the shallow aquifer. This reduction in water storage is apparently coincident with a small vertical uplift measured by the GPS data. However, no detailed multi-year seasonal analysis of the magnitude of the GPS and SG signals due to water storage effects has yet been undertaken to quantify the relation between groundwater storage and vertical deformation.

The intensive groundwater and environmental monitoring system implemented by the Overstrand Municipality around the Gateway Wellfield covers both the shallow, unconfined Bredasdorp Aquifer and the deep, confined Peninsula Aquifer. Elsewhere in the TMG aquifer regions, the network of groundwater measurement stations is spatially too limited. Furthermore, despite the current aim towards integrated water management and observation, the few specialized groundwater networks that do exist to serve local or regional water supply are often poorly integrated with other hydrological observations (e.g., streamflow). Their adequacy to provide a reliable estimate of the available groundwater resource or to measure either its depletion, or degradation of quality, is therefore doubtful. Together with the long-term SAWS/HMO weather station facility at Hermanus, the Gateway Wellfield provides an ideal "natural laboratory" setting for initial development and trial of GNSS-based space-geodetic tools for water resource monitoring and assessment.

Associated techniques

The development within South Africa of a state-of-the-art, GNSS-based technology for the precise measurement of ground deformation - whether natural or human-induced - at sub-centimetre accuracy, and its application to groundwater resource assessment and monitoring in deep fractured-rock aquifers, needs also to take account of other geophysicalgeodetic systems that have recently been developed elsewhere in the world. Among those most relevant to the TMG deep-fractured-rock environment are gravity-monitoring systems that have been used in the context of geothermal reservoir development in the United States and Japan.

Subsurface fluid monitoring is a rapidly growing application area for gravity. A change of ~3 microgals is roughly the equivalent to 1 cm of height change or 1" (2,54 cm) of subsurface water change. A change in groundwater level of several metres within a shallow aquifer that is less than 10 m thick can therefore effect a gravity change of several 10 microgal.
In this GNSS age, coordinate positions relative to the WGS84 spheroid can be determined accurately at the millimetre level, but the gravity field is generally not known well enough to determine the shape of the sea-level reference surface (geoid) to better than metres in some cases. Precise leveling with GPS instruments could be achieved over long distances with a better model of the gravity field, since first-order gravity variations are related to the shape of the geoid.

A gravity monitoring system for TMG aquifers would therefore include coordinated gravity measurement, precise levelling of survey benchmarks, in addition to measurement of groundwater level, meteorological data, and soil water content. In studies of a Japanese geothermal field at Takigami, central Kyushu (Fujimitsu et al., 2000), differences of up to 40 microgals were measured between observed and estimated gravity just after the commencement of exploitation, which showed the gravity change associated with the production and re-injection of geothermal fluid. Repeat gravity measurements were started in 1991, before the commencement of the production and re-injection at the Takigami power station.

From the results of these measurements, the background gravity change caused by seasonal changes of shallow ground water level used a multivariate regression model relating gravity to precipitation. The accuracy of these background gravity changes was about +/-10 microgals, and correlation was used to eliminate the effect of the background gravity change. Residual gravity increases of up to 10 microgals were detected in the re-injection zone, and residual gravity decreases of up to 40 microgals were detected in the production zone, consistent with the changes in mass balance in the geothermal reservoir. The technologies of both precision gravimetry and precision GNSS positioning have improved to the point where two persons can complete a field campaign of 150 benchmarks in about 20 days using both techniques (Allis, 2001). The accuracy of the gravity values should be around 5 microgals and the elevation uncertainties should be around 1 cm (Allis et al., 2000). The accuracy of horizontal movements will be better than the vertical accuracy. These accuracies, and the ease (i.e., relatively low cost) with which the measurements can be made, potentially offer new insights into the saturation (mass) changes occurring in underlying aquifers.

Significance for International Collaboration

At time scales from weeks to decades, hydrological loading of the Earth's surface dominates non-secular variation in each of three fundamental areas of geodesy: gravity field, shape, and rotation of the Earth. Space-geodetic sensors capture the signals of variation in the entire fluid envelope of the solid Earth, including the terrestrial storage of water, and their observations provide integral constraints on the water cycle at multiple spatial and temporal scales. Space geodetic observations of surface mass variability are inherently strong at regional to global scales, and could therefore be an important complement to traditional in-situ measurements of terrestrial water storage.

The Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) has the capability to monitor mass transport in the Earth system and particularly the global water cycle. The gravity satellite missions, such as the Gravity Recovery And Climate Experiment (GRACE) project, that measure the temporal variability of the Earth's gravity field are crucial to this application. However, the utilization of the full suite of geodetic observations is hampered by model insufficiencies, inconsistencies, and a lack of integration of the different space-geodetic techniques. Consequently, the dissemination of products into practical water management has not occurred.

A proposed international project on "Developing the Global Geodetic Observing System into a Monitoring System for the Global Water Cycle" (Plag et al., 2007) is currently under consideration by the UNESCO International Geoscience Programme (IGCP). The intergovernmental and international forums of the Group on Earth Observation (GEO) and GGOS, respectively, will be used to ensure sufficient satellite gravity missions, particularly with participation of emerging space agencies in Africa and Asia. Ongoing and planned research under the IGCP proposal will:

1. address the combination of space-geodetic observations, particularly GPS and GRACE-type observations, in order to exploit their individual strengths and mitigate their weaknesses;
2. improve the geophysical models for the processing of the observations;
3. enhance the extraction of highly accurate information on changes in terrestrial water storage, prepare the assimilation of the observations in integrated predictive models of the hydrological cycle, and focus on the interpretation of the space-geodetic observations in terms of regional groundwater and soil moisture changes;
4. support capacity building in the field of space-geodetic data processing, modeling of the hydrological cycle, and interpretation of the observations in terms of terrestrial water storage, through cooperation with research institutions in developing countries;
5. promote the practical use of new products for regional water management through interaction with water management authorities, particularly in developing countries,

Expected results are an improved understanding of mass redistribution in the water cycle, in particular, changes in groundwater; better exploitation of the space-geodetic observations for hydrology; and societal benefits through an improved knowledge basis for regional water management.

References

Allis RG, Gettings P, and Chapman DS (2000). Precise Gravimetry and Geothermal Reservoir Management. Proceedings 25th Workshop on Geothermal Reservoir Engineering, Stanford University, 179-188.

Allis RG, Gettings P, Isherwood WF and Chapman DS (2001) Precision Gravity Changes at the Geysers Geothermal Reservoir, 1975 - 2000, Proceedings, 26th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 29-31, 2001 SGP-TR-168.

Altamimi, Z., Sillard, P. , Boucher, C. (2002). ITRF2000 : A new release of the International Terrestrial Reference Frame for Earth Science applications. Journal of Geophysical Research 107(B10), 2214, doi:10.1029/2001JB000561.

Burbey, T.J. (1999) Effects of horizontal strain in estimating specific storage and compaction in confined and leaky aquifer systems. Hydrogeology Journal, 7: 521-532.

Burbey, T.J. (2001) Stress-strain analyses for aquifer system characterization. Ground Water, 39(1): 128-136.

Burbey, T.J. and Helm, D.C. (1999) Modeling three-dimensional deformation in response to pumping of unconsolidated aquifers. Environmental & Engineering Geoscience, 5(2): 199-212.

Calais, E., Ebinger, C., Hartnady, C., Nocquet, J-M. (2006). Kinematics of the East African Rift from GPS and earthquake slip vector data. In: G. Yirgu, C.J. Ebinger, and P.K.H Maguire (eds), The Afar Volcanic Province within the East African Rift System. Geological Society of London Special Publication 259, 9-22.

Du Preez, M., Dennis, I., and van Tonder, G.J. (2006) Experimental measurement of specific storativity by the determination of rock elastic parameters. Water Research Commission (WRC) Report Project K8/643, 53 pp.

Fujimitsu Y, Nishijima J, Shimosako N, Ehara S and Ikeda K (2000) Reservoir monitoring by repeat gravity measurements at the Takigami Geothermal Field, Central Kyushu, Japan. Proceedings World Geothermal Congress 2000 (Kyushu - Tohoku, Japan, May 28 - June 10), p. 574-577.

Hartnady, C.J.H. (2002). Earthquake hazard in Africa: perspectives on the Nubia-Somalia boundary. South African Journal of Science 98, 425-428.

Hartnady, C.J.H., Calais, E. and Wonnacott, R. (2007). ITRF2000 velocity field from the South African TrigNet GPS array and the African GNSS network: Implications for Nubia-(Rovuma-Lwandle-)Somalia plate motions. Extended abstract submitted to International Conference on the East African Rift System (EARS-07), Kampala (July 23-25), Uganda., 5 pp.

King, R.W., Bock, Y. (2005). Documentation for the GAMIT GPS software analysis, release 10.20. MIT, Cambridge, USA.

Munekane H, Tobita, M, Takasima K, Matsuzaka S, Kiroishi Y and Masaki Y (2003) Groundwater-Driven Vertical Movement in Tsukuba Detected by GPS. Eos Trans. AGU, 84(46), Fall Meet. Suppl., Abstract G52C-0049.

Plag, H.-P., Gross, R.S., Rothacher, M., Miller, N.L., Zerbini, S. and Rizos, C. (2007). Developing the Global Geodetic Observing System into a Monitoring System for the Global Water Cycle. Research Proposal to UNESCO International Geoscience Programme (IGCP), 40 pp.

Stephansson, O. (2003). Theme issue on hydromechanics in geology and geotechnics. Hydrogeology Journal, 11, 3-6.

Umvoto Africa (Pty) Ltd [Hartnady, C.J.H., Hay, E.R., Riemann, K.R., Mlisa A., Jackson, C., Paige, A., and Groenewald, L.G.] (2005). Deep Artesian Groundwater for Oudtshoorn Municipal Supply: Phase D - Target Generation and Borehole / Wellfield Siting using Structural Geology and Geophysical Methods. Water Research Commission Report No. 1254/1/05.