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MONITORING GROUNDWATER DYNAMICS WITH TIME-LAPSE GRAVITY GRADIOMETRTY: FORWARD MODELLING

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Summary

The feasibility of monitoring the depletion/recharge of ground- and surface water reservoirs using gravimetry is presented. This is important because many industrial processes are water-intensive and therefore the use of sustainable and proximate water resources is preferred.

Changes and depletion of water reservoirs must be observed with adequate water monitoring systems such as networks of monitoring wells. Water extraction or injection operations are regulated and require mandatory monitoring. Groundwater dynamics are controlled by reservoir boundary conditions and several parameters, including, but not limited to, pumping rate, hydraulic conductivity, water level/drawdown, and required monitoring intervals. Monitoring water reservoirs with gravity gradiometry is inexpensive compared to drilling a network of monitoring wells. Therefore, gravity and gravity gradient signals are forward modeled to estimate signal strength and spatio-temporal distribution of water reservoir dynamics. The required sensitivity of the gravimeters, the time intervals between measurements, and the number/density of gravity stations, are evaluated. Groundwater models for a water extraction site using ModFlow are used and the outputs are transformed to forward model a range of gravity parameters at the surface, including, vertical gravity, vertical gravity gradient, and horizontal gravity gradient.

Time-lapse gravimetry for small-scale reservoirs poses two obstacles, namely, i) a sub-microgal sensitivity requirement and ii) noise from environmental or anthropogenic sources in the vicinity of the reservoir. In principle, the use of two gravimeters in tandem could compensate for environmental noise and improve the gravity gradient measurements. Examples of reservoir models are presented to illuminate the resolvability of groundwater dynamics from surface gravity gradiometry.

Methods

Hydrogeophysics is a multidisciplinary subject focusing on the use of different techniques and geophysical methods for characterizing subsurface features, distinguishing hydrogeological properties and monitoring processes related to groundwater processes (Binley et al., 2010). Gravimetry is a geophysical method that is suitable for hydrogeophysical applications. This method can be used to provide quantitative information on the structure and fluid dynamics of the soil and subsoil (El-Diasty, 2016).

ModelMuse is used in this study to simulate the groundwater flow. It is a graphical user interface (GUI) for MODFLOW-2005, a finite-difference model simulating steady and nonsteady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined (Myhra & Rivière, 2012). The groundwater flow model is divided into packages that deal with a single aspect of simulation (Langevin et al., 2017). Groundwater models mostly use a three-dimensional combination of the water balance equation and Darcy's law (De Wiest, 1966). The modeling scheme using ModelMuse is shown in Figure 1.

The following parameters (Table 1) are assigned as inputs to ModelMuse to simulate and calibrate the groundwater model.

Table 1 Summary of MODFLOW model

No	Items	Details
1	MODFLOW VERSION	MODFLOW-2005
2	Number of Rows	15
3	Number of Columns	15
4	Width of Rows and Columns	10 m
5	Number of layers	1
6	Cells per layers	225
7	Minimum elevation	-30 m
8	Model simulation type	Steady and Transient State
9	Stress periods	40
10	Time steps	86400 seconds or 1 day
11	Stress period duration	1 day
12	Length of simulation	40 days
13	Internal flow package	Layer property flow package
14	Boundary Packages	CHD, WEL
15	Observation	Head observation
16	Hydraulic Conductivity	K_x , K_y = $1x10^{-2}$ m/s and K_z = $1x10^{-3}$ m/s

The groundwater model results in the 2D distribution of drawdown for every modeled time step. Each drawdown distribution translates into a density distribution assuming different densities for saturated and unsaturated packed sand. The density grid is then forward modeled using IGMAS+ (Interactive Geophysical Modelling Assistant). IGMAS+ is a three-dimensional interactive modeling software that processes and interprets density distributions and estimates the gravity and gravity gradient components anywhere in the model space (Schmidt, Götze & Fichler, 2010). In this study, the vertical gravity gradient (Gzz)

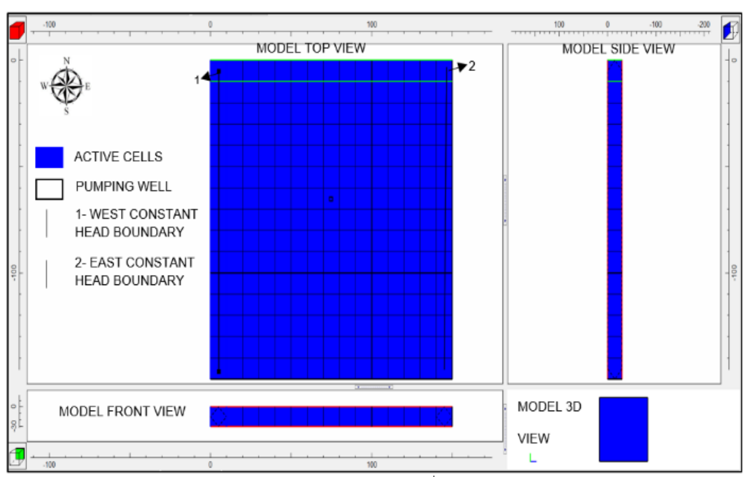

Figure 1 ModelMuse groundwater model scheme

and vertical gravity (Gz) are modeled as they are sensitive to both lateral and vertical changes in density. The Horizontal gradient (HGz) is the combination of both horizontal gravity gradients (Gxz and Gyz) and is mostly sensitive to lateral changes in density (Schmidt & Barrio-Alvers, 2014). The depth of the groundwater table from ModelMuse is imported into IGMAS+ as a 2-D surface dividing the saturated and unsaturated layers. The densities above and below the groundwater table are set to 1.6 g/cm^3 and 2.1 g/cm^3 and represent dry and wet packed sand, respectively. Gravity and gravity gradients are forward modeled for 40 aquifer models over 40 days with a varying pumping rate to estimate signal strength and directional changes of the groundwater flow.

Results

During the first 11 days of pumping with a pumping rate of 20 litres/second, the water table starts dropping down with a minimum of -2.5 m around the well. The groundwater model has a maximum gravity signal of -0.385 mGal and a gravity gradient signal of -0.8 mGal/km (Figure 2).

The signals show that there exist slight edge effects on either side of the model space due to the finite model space. However, the model was extended on either side by doubling the extend in x and y directions to reduce the edge effects. Modeling was continued based on the pumping rate as shown in Table 2.

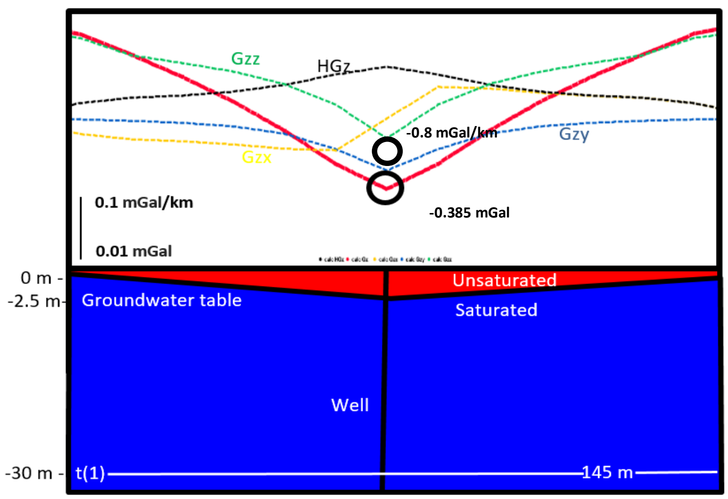

Figure 2 The forward model gravity and gravity gradient signals of the groundwater model on the first day.

The Gz signal is sensitive to vertical changes in the water table elevation. The Gz signal values of each cell are plotted over 40 days (Figure 3). From days 1 to 11, the Gz signal magnitude is approximately -0.385 mGal. The Gz signal magnitude increases to -1.150 mGal when the pumping rate is increased to 60 l/s. The next 10 days show that lowering the pumping rate to 50l/s causes weaker Gz signals, at -1.120 mGal. In the last 8 days, Gz values turn back to the beginning values, which is -0.450 mGal. The pumping rate is also overlayed in Figure 3. The changing pumping rate results in drawdown in the aquifer that turns into changes in the gravity gradient signal with a time delay. The time delays, which are shown in Figure 3 with a red dashed rectangular, are representative of the pumping rate and the rechargeability of the aquifer. The gravity signals are shown in Figure 3. The pumping rates caused changing in the drawdown , gravity and gravity gradient signals over 40 days are shown in table 2.

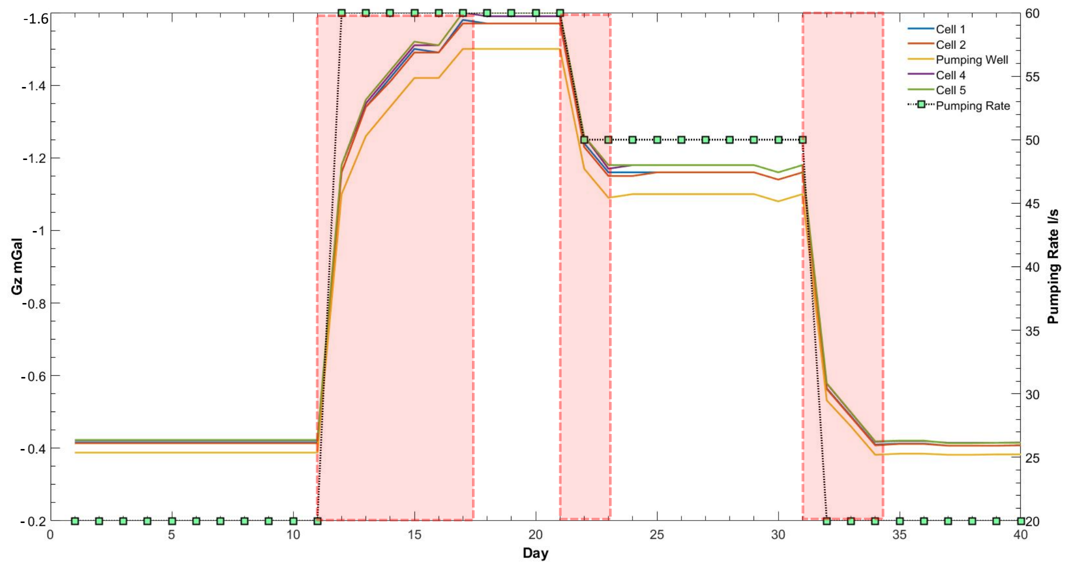

Figure 3 The vertical gravity signal (Gz) caused by changing pumping rate and pumping rate for 40 days. The location of the cells 1-5 and pumping well are given in Figure 4.

Table 2 The respective drawdown and gravity signals at the well location.

Day	Pumping Rate (l/s) [Litres/Second]	Drawdown (m)	The vertical gravity signal (Gz) [mGal]	The vertical gravity gradient signal (Gzz) [mGal/km]	The horizontal gradient signal (HGz) [mGal/km]
1	20	2.5	-0.385	-0.7	1.5
12	60	6	-1.150	-2.5	3.0
22	50	8	-1.120	-2.2	2.5
32	20	4	-0.450	-1.5	1.5

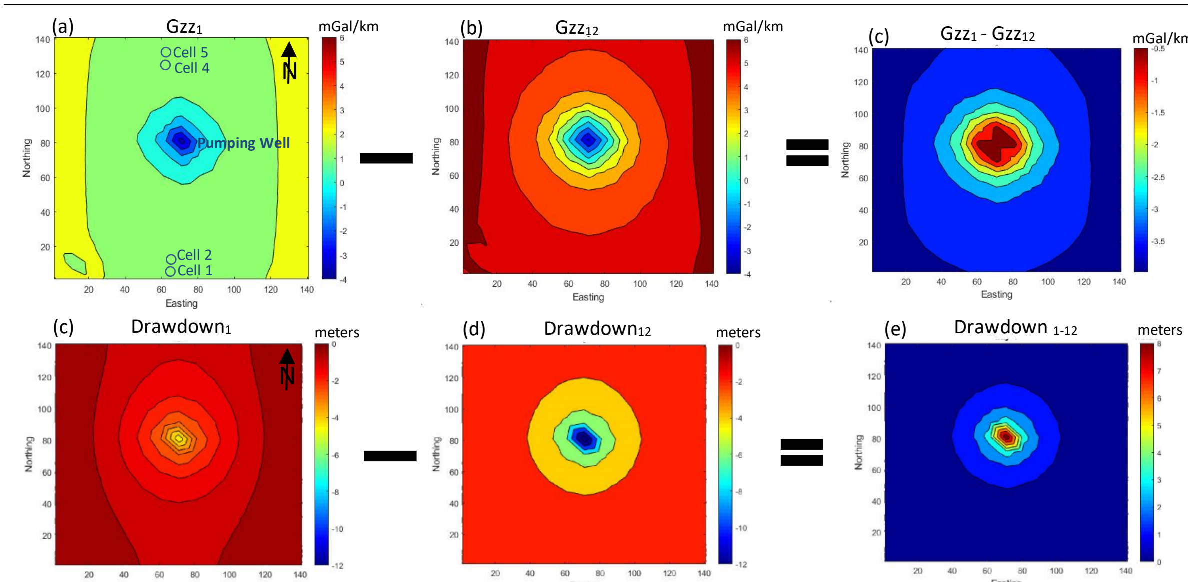

Figure 4 Gzz of the model on Day 1(a), and on Day 12(b), and their difference which shows the change in the cone of depression (c). Drawdown of the model on Day 1(c), and on day 12 (d), and their difference (e).

The cone of depression around the well is changing as a function of the pumping rate over time. The gravity signals are able to represent that change in the cone of depression (Figure 4). Using the water table on Day 1 as the reference, the differences with respect to Day 1 and later models represent the change in water volume.

Conclusions

In this study, water table drawdown due to pumping water from an aquifer was assessed with gravity gradiometry. This study indicates that the changes in a realistic groundwater flow model are significant enough to be sensed by gravity gradiometry deployed at the surface. ModelMuse helped to create the groundwater model and to alter its parameters, such as layer type, horizontal hydraulic conductivities, initial hydraulic head, constant head boundary conditions, pumping rate, stress periods to evaluate the impact of changing groundwater parameters on gravity signals. It can be concluded from the gravity gradient signals, the drawdown patterns in the model can be sensed in space and time. The gravity response also indicates a delay over time between different pumping rates. The time delay is representative of both the pumping rate and the rechargeability of the aquifer. While this model used herein is quite simple, the method employed has no limitations in performance for more complex groundwater or surface water models. Time-lapse gravity gradiometry provides a viable alternative or complement to monitoring wells and enables the monitoring of groundwater tables across a 2-D region rather than being limited to individual monitoring locations at wells. It therefore provides a more complete picture of groundwater and surface water use at a water extraction or injection site towards meeting regulatory requirements.

Acknowledgments

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References

Binley, A., Cassiani, G., & Deiana, R. (2010). Hydrogeophysics - Opportunities and Challenges. (May 2014).

De Wiest, R. J. M. (1966). On the storage coefficient and the equations of groundwater flow. Journal of Geophysical Research, 71(4), 1117–1122. https://doi.org/10.1029/jz071i004p01117

El-Diasty, M. (2016). Groundwater storage change detection using micro-gravimetric technology. Journal of Geophysics and Engineering, 13(3), 259–272. https://doi.org/10.1088/1742-2132/13/3/259

Langevin, C. D., Hughes, J. D., Banta, E. R., Niswonger, R. G., Panday, S., & Provost, A. M. (2017). Documentation for the MODFLOW 6 Groundwater Flow Model: U.S. Geological Survey Techniques and Methods. 6, 197. https://doi.org/https://doi.org/10.3133/tm6A55

Myhra, S., & Rivière, J. (2012). MODFLOW-2005,The U.S. Geological Survey Modular Ground Water Model-Documentation of Shared Noda Local Grid Refinement(LGR) and The Boundary Flow and Head (BFH) Package. Characterization of Nanostructures, 15–16. https://doi.org/10.1201/b12176-3

Schmidt, S., Götze, H. J., & Fichler Ch., A. M. (2010). IGMAS+: a new 3D gravity, FTG and magnetic modelling software. Extended abstract. Geoinformatik, 12(January 2010), 57–63.

Schmidt, S., & Barrio-Alvers, L. (2014). Igmas+ Manual.