Roinn Cumarsáide, Gníomhaithe ar son na hAeráide & Comhshaoil
Department of Communications, Climate Action & Environment

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Suirbhéireacht Gheolaíochta
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Research Programme
- Short Call 2020, Final Report -

Lead Applicant Name	Ulrich Ofterdinger
Host Organisation name	Queen's University Belfast
Project Title	Groundwater-g - Supporting Groundwater Resources Management using Low-Cost Microgravity Technology
Contract Number	2020-sc-003

This report covers the period 1st December 2020 to project end date 31st August 2022

2. (a) Project information:

Final project report (*max 2500 words, excluding figures and headings*):

Executive summary (lay abstract, approx. 250 words):

The project investigated the field application of a new microgravity sensor technology ('gravimeter-on-a-chip' using a microelectron-mechanical system – MEMS) as a non-invasive low-cost tool for monitoring fluctuations in groundwater storage in Irish aquifers. The project completed microgravity field campaigns at a number of study sites coinciding with existing groundwater monitoring Installations across different aquifer typologies. The project allowed for the first time to test the device under realistic adverse field conditions for environmental applications (strong winds, rain, and cold temperatures).
While an earlier version of the sensor device faced significant challenges in the field application, a more advanced version of the sensor device available for later surveys was able to successfully detect groundwater storage fluctuations and allowed the estimation of aquifer storage properties. The conducted field tests also highlighted that the sensor is capable of resolving groundwater storage changes within the typical range associated with seasonal fluctuations. The invaluable experience and data collected during the field deployment of the sensor under realistic (adverse) field conditions has allowed for the advancement of the device providing for a more robust sensor platform. The success in detecting groundwater storage fluctuations is very encouraging and provides a basis for further developing the field deployment of the sensor as a promising low-cost tool for groundwater monitoring.

(i) Results, scientific/engineering targets reached beyond the state of the art and conclusions

The objectives of the project focused on investigating the field application of a new microgravity sensor technology ('gravimeter-on-a-chip' using a microelectron-mechanical system – MEMS; Middlemiss et al. 2016, 2018) as a non-invasive low-cost tool for monitoring fluctuations in groundwater storage in Irish aquifers. The gravity method is a non-destructive geophysical technique that measures differences in the Earth's gravitational field. Variations of densities of subsurface masses produce variations in the measured gravity field. Ground-based time-lapse gravity is a promising method for quantifying subsurface water-content change (Pool and Eychaner 1995; Kennedy 2015) and determining aquifer properties, e.g. specific-yield in unconfined aquifers

(Pool 2008, Damiata and Lee 2006). Ground-based gravity measurements typically integrate water storage change at a scale (10s to 100s meter) relevant to catchment scale water resource management. Ground-based gravity measurements can thus be used to estimate local to regional variations in groundwater mass associated with a rise or fall in the water table (Montgomery at al. 1971, Pool & Schmidt 1997, Howle et al. 2003), e.g. detecting gravity changes in the order of 10s-100s µGal (1µGal=1cm/s2, e.g., Gehman et al. 2009). However, commercially available portable gravimeters deployed in ground-based surveys are heavy and expensive (>€100K), limiting their practical application in groundwater monitoring. The recent invention of the new MEMS gravimeter provides an exciting new sensor which may overcome these limitations at a fraction of the cost (<€5K).

The project set out to complete microgravity field campaigns and long-term monitoring using the new low-cost MEMS gravimeter technology at a number of study sites coinciding with existing Groundwater Monitoring Installations. However since the beginning of the Project in December 2020, the Covid-19 restrictions throughout 2021 significantly impacted on the commencement and progression of the project. Covid-19 related travel restrictions imposed in Ireland and the UK in the first half of 2021 meant that joint fieldwork at the study sites was not possible during those restricted periods. More importantly, the limitations on access to laboratories and clean-room facilities at the University of Glasgow associated with the Covid-19 restrictions led to delays in the manufacture of the MEMS gravity sensors. Furthermore, ongoing supply chain delays for microchips (ADC microchips are a key component for the sensor) throughout 2021 continued to impact on the sensor manufacturing. As a consequence, the availability of new sensors for deployment in the field was limited during 2021/22. To address this challenge, the project pivoted its focus to the short-term deployments of the available sensor to monitor groundwater storage changes imposed on the study aquifers by active pumping tests at the study sites rather than the long-term seasonal field deployment of the sensor.

To this end, the project completed a 2021 field campaign at the Nueanna and Dripsey study sites with an early prototype of the sensor. An improved version of the sensor was deployed for a 2022 field campaign at the Shanmoy and Mount Stewart study sites.

The Nuenna microgravity study site is located at the “NU2” EPA groundwater monitoring location within the Nuenna catchment in Co. Kilkenny (Fig. 1). The subsurface at this location comprises brown earths and podzolic soils overlying alluvial gravels (up to 8m thickness). The underlying bedrock geology is pure bedded Dinantian limestone. The groundwater well installations at this EPA monitoring location include three separate monitoring wells targeting the subsoils, the shallow bedrock and the deep bedrock with installation depths of 9.3m bgl, 27.4m bgl and 79.5m bgl, respectively (Moe et al. 2010, Orr et al. 2016).

Figure 1: (a) & (b) Location of Nuenna Study Site and (c) & (d) Field Deployment of Sensor Deivce

The Dripsey microgravity study site is located at the "DR2" EPA groundwater monitoring location within the Dripsey catchment in Co. Cork (Fig. 2). The subsurface at this location comprises brown earths and podzolic soils overlying Devonian Old Red Sandstone. The groundwater well installations at this EPA monitoring location include three separate monitoring wells targeting the transition zone, the shallow bedrock and the deep bedrock with installation depths of 5.9m bgl, 16.15m bgl and 60.96m bgl, respectively (Moe et al. 2010).

Figure 2: (a) & (b) Location of Dripsey Study Site and (c) Field Deployment of Sensor Device

Constant rate pump tests were completed in each of the monitoring wells at both sites. Groundwater levels during the active test and the recovery phase were monitored with automated data loggers and manual control measurements. The microgravity sensor was set up next to the respective monitoring well (Fig. 1 & 2). Microgravity data collection included baseline readings prior to the commencement of the active test, the active pump test phase as well as the subsequent recovery phase. The summary details of the completed pump tests are summarised in Table 1.

Table 1: Summary of pump test details for the Nuenna and Dripsey study sites as well as estimated gravity signal following the Bouguer Slab Model associated with the observed maximum drawdown in the respective aquifer unit and assumed specific yield (Sy).

Study Site	**Pump Rate [l/min]**	**Observed max. Drawdown [m]**	**S_y [.]**	**Estimated Gravity Signal [μGal]**
NU2_subsoil	30	3.08	0.25[b]	110
NU2_shallow bedrock	30	- [a]	-	-
NU2_deep bedrock	30	19.00	0.14[b]	30
DR2_transition	10	1.66	0.20[b]	14
DR2-shallow bedrock	10	12.34	0.10[c]	51
DR2_deep bedrock	10	2.00	0.03[c]	3

a - pump test terminated due to sensor malfunction
b - assumed value according to Johnson (1967) and Kelly et al. (2015)
c - assumed value for Old Red Sandstone close to surface and at depth, respectively after Ó Dochartaugh et al. (2015) and Jones et al. (2000).

To relate the time-lapse microgravity data to water-storage changes, the most common approach calculates the gravity effect of one-dimensional storage change. In this simplest case storage changes occur at a flat water table and groundwater mass change can be parameterized as equivalent water thickness from the Bouguer slab equation [Telford et al., 1990]:

$$\Delta h = \frac{\Delta g}{2\pi\rho\delta} \qquad (1)$$

$$\Delta h = \Delta z S_y \qquad (2)$$

where Δz is the change in water table elevation, Δh is the thickness of an equivalent layer of water of infinite spatial extent that is required to produce the measured change in gravity (in other words, it is the change in groundwater volume per unit area), Δg is the change in gravity, ρ is the density of water, δ is the universal gravitational constant (6.67 x 10^{-11} N m^2 kg^{-2}) and S_y is the specific yield. As a first estimate using this simplified approach, and assuming respective values for specific yield (S_y) for the individual aquifer units, the expected microgravity signal associated with the observed drawdowns may be estimated (Table 1).

Unfortunately, the collected microgravity sensor data collected during the pumping tests at the Nuenna and Dripsey site showed to be inconclusive. Repeated communication problems between the sensor device and the controlling IT equipment in the field led to repeated loss of data. This was mainly linked to problems with the wired connection under wet field conditions. Furthermore, the generator operated external power source used for the sensor in the field led to an increase in noise in the data set data at both study sites. Additionally, the pump testing in the low permeable bedrock aquifers at the Nuenna and Dripsey sites is likely to have resulted in a narrow steep cone of depression around the abstraction wells. This rather localised change in groundwater storage may have also been more difficult to be resolved with the sensor. The more complex shape of the imposed water table change due to completed pump tests in these low permeable aquifers may also make the above Bouguer Slab Model less applicable to these environments.

Subsequent to the 2021 field campaign with an early version of the sensor, a further advanced, more ruggedized version of the microgravity sensor was developed. This sensor allowed the wireless communication (Bluetooth) between the sensor unit and the controlling field laptop, thus reducing the communication problems under field conditions. The sensor was furthermore equipped with internal batteries, which in turn provided a more stable power supply to the sensor.

In order to improve the chances of detecting meaningful changes in groundwater storage during pumping tests, the project deployed the new sensor at two study sites with higher productive aquifers units, ie. the Shanmoy and Mount Stewart study sites.

The Shanmoy study site is located at a former Northern Ireland Water (NIW) groundwater production well (BH5) South of Dungannon, Co. Tyrone (Fig. 3). The well is currently being investigated in the context of potentially recommissioning groundwater abstraction for drinking water supplies at this location. The project was able to combine the microgravity monitoring with a step-drawdown test in BH5 completed by TetraTech on behalf of NIW. The subsurface at the site comprises alluvial sand & gravel deposits overlying the Triassic Sherwood Sandstone. The monitoring well is completed within the sand & gravel deposits to a total depth of 18.9m.

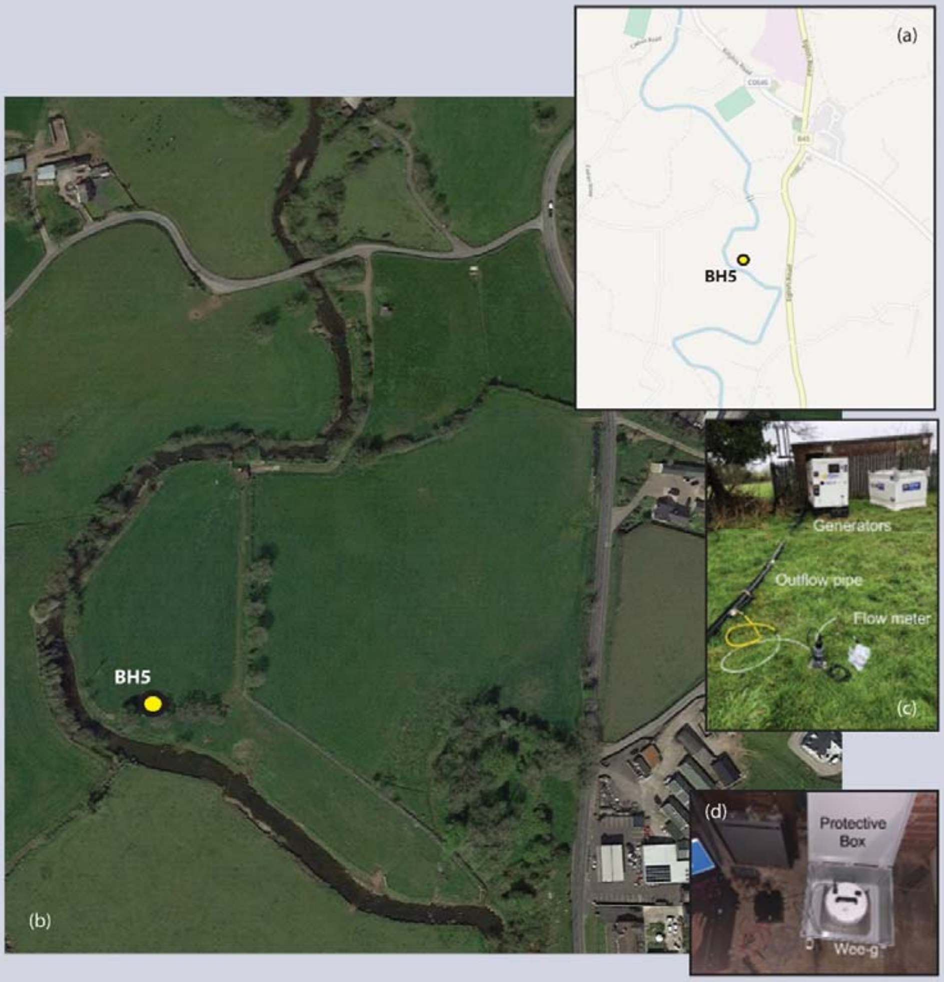

Figure 3: (a) & (b) Location of Shanmoy Study Site; (c) Setup of Pumptest at BH5; (d() Field Deployment of Sensor Deivce in pump house at BH5

A step drawdown test was completed in the well with pumping rates of 1,395 m^3/d, 1,961 m^3/d and 2,453 m^3/d, respectively (1 hour each). Groundwater levels during the active test and the recovery phase were monitored with automated data loggers and manual control measurements. The microgravity sensor was set up next to the monitoring well and microgravity data collection included baseline readings prior to the commencement of the active test, the active pump test phase as well as the subsequent recovery phase. The pump tests led to maximum observed drawdowns in the wells of 7.45m in the sand & gravel deposits.

While the collected microgravity data from the active pumping phase of the test is impacted by noise from the operation of the electrical submersible pump, the microgravity data recorded during the recovery phase after pump shut-off shows a clearer trend of rising gravity values as groundwater levels at the site recover towards baseline values (Fig. 4). Individual larger spikes in the gravity data throughout the monitoring period are related to microseismicity associated with walking in close proximity to the sensor during manual water level measurements. The noticeable spike at the end of the pumping / beginning of the recovery phase is related to the shut-off of the pump.

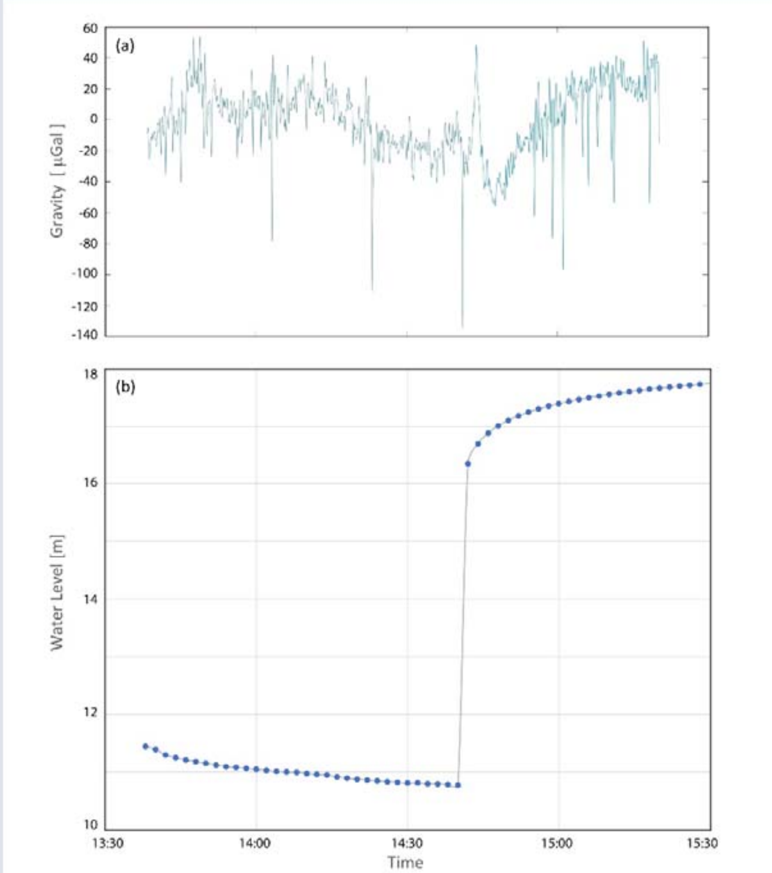

Figure 4: Field Obsevations during late pumping and early recovery phase at BH5 (Shanmoy); (a) microgravity data and (b) water level data

Using the observed groundwater level changes during the recovery phase and the microgravity data recorded during this phase it is possible to estimate the storage properties of the sand & gravel aquifer at the site. Following the simple Bouguer slab model outlined earlier and using the observed water level changes of 7.5m and the associated change in gravity of approx. 90 µGal, a value of 0.29 can be calculated for the specific yield (S_y) of the sand & gravel aquifer using Eq. 1 and 2. This value lies within the typical observed range for this type of unconsolidated aquifer, with value ranging from 0.2 to 0.31 (Johnson 1967, Kelly et al. 2015). To this end, the field test at the Shanmoy site demonstrated how the new microgravity sensor may be used to determine aquifer storage properties, which in turn may be employed to constrain groundwater models for water resources management as shown by Kennedy et al. (2022).

The Mount Stewart study site is located at the groundwater monitoring well BH7 on the National Trust Mount Stewart Estate, Co. Down (Figure 5). The subsurface at the site comprises shallow gravelly clay overlying the Triassic Sherwood Sandstone. The groundwater monitoring well BH7 is completed within Sherwood Sandstone to a total depth of 45m. A constant rate pump tests with a nominal flow rate of 30 l/min was completed in the monitoring well. Groundwater levels and microgravity data during the active test and the recovery phase were monitored similar to the other study sites. The pump tests led to maximum observed drawdowns in the well of 4.36m.

Figure 5: (a) & (b) Location of Mount Stewart Study Site and (c) Field Deployment of Sensor Deivce

As a first estimate using this simplified Bouguer slab model approach (Eq. 1 & 2), and assuming a value for *Sy* of 0.1 – 0.3 for the Sherwood Sandstone (Comte et al. 2017), the expected microgravity signal associated with the observed drawdowns may lie in the order of 18 – 54 μGal for the observed changes in groundwater levels.

Unfortunately, the collected microgravity sensor data collected during the pumping tests at the Mount Stewart did not show any conclusive changes that may be associated with the groundwater abstraction. It is likely that the drawdown imposed by the pumping test was not sufficiently extensive to be detected by the microgravity sensor.

Conclusions

Previous studies by the University of Glasgow (UoG) Team have employed the new microgravity sensor for conducting gravity surveys in and around the UoG campus under controlled conditions. This project allowed for the first time to test the device under more realistic field conditions for environmental applications, ie. groundwater storage monitoring. This including the transport to site (by car and ferry) and the field deployment of the device under adverse weather conditions (strong winds, rain, and cold temperatures).

The field deployment of the early version of the sensor device at the Nuenna and Dripsey sites faced significant challenges. While the expected microgravity data associated with the imposed drawdowns were within the resolution of the sensor, conclusive measurements were not recorded due to multiple malfunctions of the early device in the field.

The more advanced version of the sensor device was able to successfully detect groundwater storage fluctuations at the Shanmoy site which in turn allowed the estimation of aquifer storage properties. The conducted field tests also highlighted that the sensor is capable of resolving groundwater storage changes within the typical range associated with seasonal fluctuations. The invaluable experience and data collected during the field deployment of the sensor under realistic (adverse) field conditions has allowed for the advancement of the device providing for a more robust sensor platform. The success in detecting groundwater storage fluctuations with the advanced version of the sensor is very encouraging and provides a basis for further developing the field deployment of the sensor as a promising low-cost tool for groundwater monitoring.

(ii) Implementation (milestones, deliverables, project management)

The commencement and progress of the project had been significantly impacted by the Covid-19 restrictions throughout 2021. Covid-19 related travel restrictions imposed in Ireland and the UK in the first half of 2021 meant that joint fieldwork at the study sites was not possible during those restricted periods. More importantly, the limitations on access to laboratories and clean-room facilities at the University of Glasgow associated with the Covid-19 restrictions led to delays in the manufacture of the MEMS gravity sensors available to the project. Furthermore, ongoing supply problems for microchips (ADC microchips are a key component for the sensor) throughout 2021 continued to impact on the sensor manufacturing with knock-on delays into the later part of 2021 and early 2022. As a consequence, the availability of new sensors for deployment in the field was significantly limited during 2021/22.

Microgravity field surveys using an early prototype version of the sensor device were completed in Q3 2021 in collaboration with the project partners at QUB, UCC, UoG and UoA, including academic and junior research staff from the partner institutions. A further campaign of microgravity surveys using an advanced version of the sensor device was completed in Q2/3 2022 by the project partners. Collected microgravity and groundwater monitoring data were processed subsequent to the completed fieldwork and an internal summary report outlining the data collection, processing and interpretation was completed by all partners during Q3 2022.

The new microgravity sensor technology, its applications in hydrogeology and the project outcomes were presented at a project stakeholder workshop (September 2022). A first paper manuscript is currently being developed by the project partners on the field applications of the microgravity sensor device which will include the project outcomes (see below). Furthermore, a joint presentation on the field application of the microgravity sensor for environmental monitoring is planned for the AGU Fall Meeting 2022 (see below).

(iii) Outputs to date

- Demonstration Project for the application of new low-cost microgravity technology to monitor groundwater storage fluctuations and measure aquifer parameters across Irish bedrock aquifers;
- Field microgravity data for benchmarking MEMS sensor technology;
- Training of Junior Research Staff in the application of the microgravity survey method;
- Presentation of new MEMS sensor technology and microgravity applications in Aquifer Monitoring & Characterisation to the wider community of hydrogeology practitioners and researchers;
- Preparation of Conference Presentations (see below);

- Preparation of Joint Journal Publication (see below).

Field data sets are currently held jointly by the project partners and will be published in the following presentations/publications which are currently being prepared:

Anastasiou, K., Middlemiss, R., Ofterdinger, U., Weatherill, J., Comte, JC., Hammond, G., 2022, Field Applications of a new MEMS gravimeter, *AGU Fall Meeting*, 12-16 December 2022, *in prep*

Prasad, A., Toland, K., Middlemiss, R., Ofterdinger, U., Weatherill, J., Comte, JC., Anastasiou, K., Utting, P., Hammond, G., 2022, Environmental Field Applications of a MEMS gravimeter, *Nature*, *in prep*

(iv) Impact

- Relevance/application to GSI programmes, where applicable

The Groundwater-g project demonstrated the field application of a new low-cost gravimeter for applications in hydrogeology. While an early prototype of the sensor experienced technical challenges in the field deployment, a more advanced version of the sensor was able to monitor groundwater storage changes associated with groundwater abstractions and within the range of water level fluctuations that may also be expected for seasonal variations in groundwater storage. To this end, the project highlighted the new sensor technology as a promising tool for groundwater monitoring and future application of the new sensor technology across Irish catchments may allow for a more comprehensive monitoring and managing of groundwater resources in line with one of the key objectives of the GSI Groundwater Programme.

- Other impacts

The Groundwater-g project provided leverage for follow-on funding applications by the project partners to further establish the use of the sensor technology in groundwater management practice and research.

The Project partners secured funding under the UKRI-GCRF Networking Programme to further test the deployment of the sensor technology for groundwater storage monitoring with research partners and water management authorities in Burkina Faso, Kenya and South Africa (£30K). The partners furthermore submitted a follow-on application to UKRI / NERC under the 'Exploring the frontiers of environmental science research' Programme to establish a number of long-term catchment monitoring stations across Scotland and the Island of Ireland for the deployment of the new sensor device (£100K, pending).

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