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# GRACE Monitoring of Groundwater Over Ireland – A Feasibility Study

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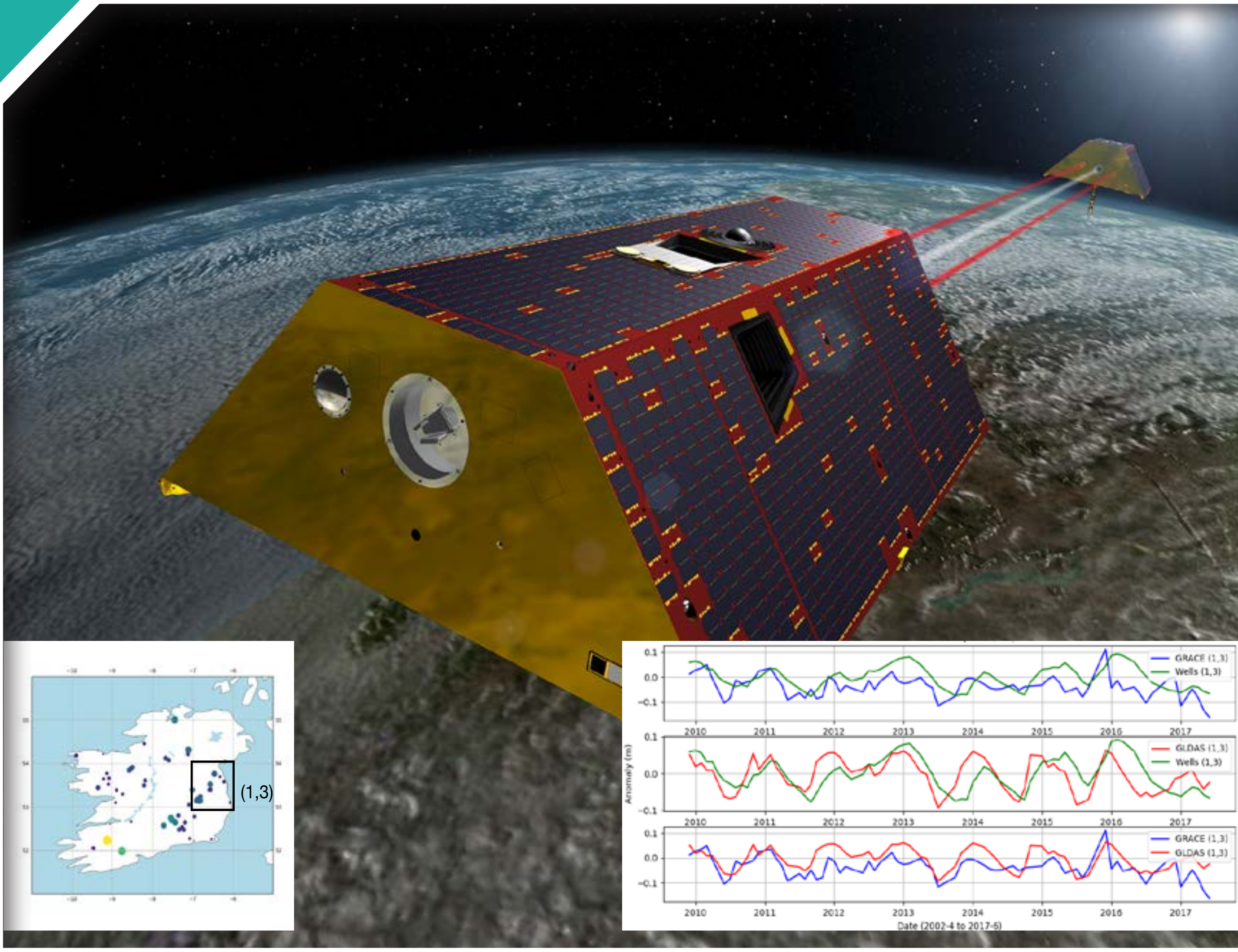

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EPA RESEARCH PROGRAMME 2021–2030

# GRACE Monitoring of Groundwater over Ireland – A Feasibility Study

## (2018-W-DS-33)

## EPA Research Report

Prepared for the Environmental Protection Agency

by

National University of Ireland Galway

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This report is based on research carried out/data from 1 May 2019 until 1 July 2020. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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# Executive Summary

This 1-year desk study investigates the feasibility of using satellite measurements from low Earth orbit to monitor groundwater variations over Ireland. Data from the National Aeronautics and Space Administration's (NASA's) Gravity Recovery and Climate Experiment (GRACE) mission are combined with surface moisture estimates from NASA's Global Land Data Assimilation System (GLDAS) 0.25° resolution land surface model to infer the groundwater anomaly as detected by the satellites at 1° latitude–longitude resolution, and this signal is then compared with groundwater levels measured by the Environmental Protection Agency (EPA) HydroNet network of monitoring wells. The resulting measure, known as the terrestrial water storage (TWS) anomaly, represents the total water anomaly variation over a 1-month period, and is generally given in units of length (depth) per unit pixel area, allowing a total estimate to be derived per study area in units of volume. At Ireland's latitude, the pixel scale is ~110 km × 70 km.

Groundwater estimation using GRACE data has typically been applied to continental and large regional scale environments, typically river basins in Amazonia and in equatorial Africa, and the locations of known aquifers such as the Indus basin aquifer. These areas span regions in excess of 100,000 $km^2$ and are associated with significant changes in groundwater, from either seasonal cycles or intense and sustained abstraction. This contrasts with the Irish context, where the island's total surface area is ~84,421 $km^2$ and its largest river basin, that of the Shannon, encompasses ~17,000 $km^2$. Furthermore, Ireland's dominant bedrock aquifer environment coupled with its temperate oceanic climate ensuring consistent precipitation patterns might reasonably be expected to produce only moderate impulse events in localised groundwater abstraction/recharge, limiting the likelihood of detection from orbit.

However, studies in continental Europe have demonstrated the utility of GRACE observational data on smaller scales, and several studies have directly correlated variations observed from orbit with localised groundwater well measurements, with the latter being used as a baseline for the process of downscaling the inferred groundwater signal, down to tens of km in some cases. Prior to exploring the use of a similar downscaling strategy in an Irish context, the properties of inferred total surface water and then inferred groundwater variations need to be determined.

We implemented best practice by removing the modelled surface water contribution to a depth of 2 m, as determined by NASA's GLDAS land surface model, from the GRACE analysis-ready data, and selected four pixels spanning the cardinal points of the island that also host several EPA HydroNet groundwater wells, to explore inferred groundwater variations at these four hydrogeological locations from orbit. Our work demonstrates very good agreement between the total inferred water variations determined from orbit, the GLDAS land surface model estimates and the actual groundwater well measurements. The data also indicate the relative stability and potential long-term stability of the groundwater environment, on the broadest spatial scales, across the country – we could see no long-term evidence of depletion, particularly in the eastern region. We also identified a lead of ~1 month between the GRACE and GLDAS signals and the actual groundwater well measurements for those pixels associated with known productive bedrock aquifer zones in the south and east of the country; however, the precise lead time is constrained by the monthly cadence of the GRACE data products, which limits our ability to better resolve this timescale.

The inferred groundwater signal alone, taken to be the contribution at a depth greater than 2 m as defined by the GLDAS model, showed no such correlations with the groundwater well data. The failure to obtain a viable groundwater signal from the GRACE data is likely to have two causes. The first is that the true varying groundwater storage determined over a monthly period does not generate a significantly large signal for detection above a more dominant "surface" water component. The second is that the GLDAS land surface model fails to accurately capture the complex Irish "surface water environment", in particular those parts of the landscape dominated by peat bogs and loughs.

However, the consistent agreement between the GRACE observations, GLDAS model predictions and groundwater well measurements does offer an alternative conclusion, namely that, broadly speaking, there is concordance among all three, that groundwater variations in Ireland are coupled to surface perturbations, and that efforts to study groundwater variations may best be made by investing in a more accurate and context-specific land surface model for the island and focusing on finessing its future performance – and utility – through comparisons with the existing groundwater well network.

# 1 Introduction

## 1.1 Objectives

This report documents a desk study assessing the utility of remotely sensed estimates of groundwater variation in an Irish context by means of an analysis of gravitational anomaly data obtained from the National Aeronautics and Space Administration (NASA) and German Aerospace Centre (DLR) Gravity Recovery and Climate Experiment (GRACE) mission. Although there is an existing network of groundwater wells operated by the Environmental Protection Agency (EPA) and Geological Survey Ireland (GSI) within Ireland, their operation has been more oriented around the assessment of groundwater quality (EPA) and quantity/hydrogeological context (GSI) as part of the relevant directives, rather than the study of groundwater variation from a national hydrological perspective. However, given the greater demands on groundwater resources, particularly in the midlands and eastern part of Ireland associated with both population growth and industrial/agricultural development in these regions, combined with the localised impact of climate change, the question of whether GRACE observations could capture groundwater variations nationally and regionally is a pertinent one to ask, and formed the basis of this project.

In this report, we place the use of GRACE observations in the context of studying terrestrial groundwater variations, briefly outlining the means by which such gravitational anomalies are determined, how the resulting groundwater signals are discerned and the success that other researchers have had in assessing such variations remotely compared with what has been determined locally via groundwater well measurements. We then describe the specific circumstances of the Irish context of the study and outline the methodologies we adopted in both processing archival GRACE data and the management and processing of the EPA's groundwater well data. Subsequent analyses of these data permitted the assessment of groundwater variation correlations, on differing spatial scales on the island, between remotely sensed and ground truth estimates of groundwater variation. We conclude with our assessment of the use of GRACE to monitor groundwater in an Irish context, and provide a means for interested parties to access and reproduce the analyses conducted as part of this study.

## 1.2 Groundwater in an Irish Context

Access and use of groundwater supplies in Ireland play a significant and growing role in the use of this natural resource for both domestic and economic/industrial usage. Estimates at the turn of the century that groundwater constituted up to 25% of all supply, with over 200,000 groundwater wells in operation (EPA, 2003), can be considered the lower bounds given the significant economic development and population growth since then. Securing the integrity of all water supplies in Ireland is mandated by the Drinking Water Regulations[1] and more generally the Water Framework Directive[2] (Directive 2000/60/EC) and the Groundwater Directive[3] (Directive 2006/118/EC). Therefore, the EPA, working with colleagues at the GSI and Teagasc, have for almost two decades implemented a range of activities to monitor local groundwater quality, as well as to integrate our understanding of the underlying aquifer properties to better inform policy and safeguard this national resource.

Work to date has been focused on regular monitoring of the underlying aquifer system(s) using the National Groundwater Monitoring Network via the automated operation of several hundred groundwater wells

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[1] ISB, S.I. No. 122/2014 – European Union (Drinking Water) Regulations 2014, http://www.irishstatutebook.ie/eli/2014/si/122/made/en/print (accessed 12 March 2021).

[2] https://ec.europa.eu/environment/water/water-framework/index_en.html (accessed 12 March 2021).

[3] https://www.eea.europa.eu/policy-documents/groundwater-directive-gwd-2006-118-ec (accessed 12 March 2021).

providing both quality (in terms of contaminants) and level (i.e. depth) data. This information, combined with local geological, climatic and urban development data, provides a framework with which regulatory authorities can determine threshold values relevant to local water quality and also assess evidence for over-abstraction of the local aquifer environment.

Opportunities exist to integrate this information into our understanding of groundwater flow from the aquifer types, local structural geology and proximity to lakes and transitional and coastal waters. However, a key missing piece in the puzzle is the means of being able to more rigorously assess the spatial distribution of the underlying aquifer systems in Ireland, and, in so doing, develop more effective means of not only flagging up genuine stress events – as distinct from natural variations – in local groundwater supply, but also predicting groundwater storage over time, locally and at a regional level. To do this requires a means of sampling the actual groundwater body itself, and then of tying this to measurements obtained locally, yielding quantitative means to achieve these goals.

Such measurements are of relevance in the context of climate change. Modelling analyses suggest that seasonal trends will dominate precipitation patterns across Ireland, and that precipitation patterns will be exacerbated by regional location. For example, winter precipitation is expected to increase from the previous century's baselines by 2.2% ± 1.5%, with reductions in summer precipitation of the order of 8.5% in the 2020s, and by up to 13% ± 3% along the eastern and southern coasts (Williams and Lee, 2008). These changes, combined with the changing patterns of precipitation generally, i.e. from less of a continuum to more localised, impulsive precipitation events, are expected to have an impact on the ability of groundwater reserves to recharge to their equilibrium states. When one then factors in the growth in the Irish population, the gradual migration to urban regions (particularly to the Dublin metropolitan region) and the associated increase in the industrial and agri-food sectors in the southern and eastern parts of the country since the turn of the millennium, the ability to independently capture evidence of unusual or consistent deviations from normal seasonal flows on regional or finer scales on the island of Ireland directly from orbit offers a comprehensive means of highlighting unambiguous stresses on indigenous groundwater resources.

## 1.3 The GRACE Mission

### *1.3.1 The GRACE and GRACE-FO satellites*

Remote sensing of gravitational anomalies from low Earth orbit offers the means to holistically capture an extended spatial region's groundwater surface and behaviour, and forms the basis of the NASA/DLR GRACE mission. Initially operating from 2002 to 2017, and with GRACE-Follow-on (GRACE-FO) launched in May 2018, the mission concept involves a pair of spacecraft orbiting in close proximity some 220 km apart; deviations in their separation following the same orbital meridian (89° inclination at an altitude of 500 km) as measured from their own individual reference frames can be inverted to determine the underling gravitational anomaly at points on the Earth's surface along the flight path. Such anomalies, having been corrected for atmospheric, oceanic and the planet's static gravitational field contributions, are dominated by changes in terrestrial water. By tracking differences over time, the trends in groundwater variations become apparent. Thus, the GRACE missions do not provide a direct measure of groundwater at a given location, rather they indicate the changing volume of groundwater at a given location, over a given time frame. The spacecrafts' relative positions with respect to their own inertial reference frames, along with their absolute positions as a function of time orbiting the Earth, constitute the raw Level 1 (L1) data received by participating ground stations for subsequent analysis.

### *1.3.2 How gravitational anomalies are determined using GRACE/GRACE-FO data*

The process of inversion used to determine such anomalies is, however, a non-trivial mathematical exercise and involves the use of spherical harmonic analysis to capture the anomaly variations over each orbital pass, with the "resolution" of the smallest detectable harmonic (or gravitational anomaly on the geoid) being a function of the order of the coefficient expansion applied, usually up to degree and order 120. To ensure adequate sampling of the entire geoid, and given the limited meridional coverage of each orbital pass, the inversion process is applied to yield monthly derived solutions, and incorporates the use of spatial/temporal filters to limit the impact of what is an intrinsically noisy dataset with a strong north–south striping bias due to the satellites' orbit. Clipping functions attempt to capture the discrete change from ocean to land, but some overlap in signal is unavoidable at such boundaries. The resulting resolution is 1° square. Raw L1 data from the spacecraft is processed by three separate facilities, NASA/Caltech's Jet Propulsion Laboratory (JPL), the University of Texas Center for Space Research (CSR) and the GeoForschungsZentrum (GFZ) in Potsdam, Germany. Each facility implements differing approaches to the same common methodology, yielding Level 2 (L2) data that capture the varying geopotential as modelled by spherical harmonic analysis yielding sets of Stokes coefficients per sampling interval. These L2 data are then further processed to derive GRACE's Level 3 (L3) data products, known collectively as the GRACE Tellus–Land release RL05 monthly mass 1° × 1° grid data.

An alternative approach to characterising observed gravitational anomalies is to use a technique pioneered in planetary astronomy, namely the "mascon" or mass concentration technique. In contrast to the use of spherical harmonics, which attempt to fit the global gravitational field using a superposition of spherical functions, the mascon technique uses a priori localisation of 4551 equal-area 3° mascon values, in effect offering a more powerful means of deconvolving variable gravitational anomalies without the need for clipping functions and so on. These data are presented as surface mass changes with a 0.5° spatial resolution (~56 km at the equator), which represent subsampling of the original 3° mascon values and so imply a lack of true independence between neighbouring mascon solutions. Mascon solutions are generated by the University of Texas CSR (0.5° × 0.5° grid), NASA's Goddard Space Flight Center (GSFC) (1° × 1° grid) and NASA/Caltech's JPL (0.5° × 0.5° grid), with time-invariant scaling factors provided for only the JPL mascon data.

There have been two GRACE missions – the original (2002–2017) and the GRACE-FO mission, which started in 2018 and continues to this day. GRACE-FO has a design lifetime of 5 years; however, budget extensions to the mission are very likely, assuming both spacecraft are operating successfully in 2023. The original GRACE mission had an initial 5-year design lifetime yet delivered quality data for 15 years in total. Most analyses presented in the literature are based on data collected during the initial mission. In 2011, technical issues associated with on-board power resulted in the degradation of the mission performance and the data quality was noticeably reduced; the mission ended in 2017, when both satellites were de-orbited following the failure of battery subsystems on both spacecraft.

### *1.3.3 How groundwater storage variations are determined from GRACE terrestrial water storage observations*

The GRACE missions provide an absolute measure of time-varying gravitational anomalies evident from orbit, having taken account of all other varying atmospheric and oceanic components. Assuming planetary mass variations remain static over the monthly sampling period, and having corrected for marine, tidal and atmospheric water variations, all subsequent inferred variations are assumed to be a consequence of groundwater movement. The processed GRACE solutions are made available in the form of terrestrial water storage (TWS) anomalies, corresponding to liquid water equivalent (LWE) thickness in centimetres on a regular grid derived from either spherical harmonic or mascon-based solutions. For the former methodology, extensive analysis based on comparisons with well-controlled and sampled continental-scale aquifer systems whose abstraction/recharging variations are well characterised has determined that the error on the GRACE-derived LWE thickness is estimated to be at best 2 cm for a catchment area of ~63,000 km$^2$ (Vishwakarma *et al*., 2018).

The actual variable groundwater component is computed by subtracting the other variable water components known or inferred from a specific spatial location. These latter water estimates can be obtained from the Global Land Data Assimilation System (GLDAS) Noah model, as recommended by the GRACE L3 Data Product User Handbook (Cooley and Landerer, 2019). GLDAS is a global, high-resolution (0.25°) land surface modelling system that integrates remote sensing and terrestrial observations to produce near real-time maps of land surface states and fluxes for predicting the responses of water resources to climate variations, and provides global estimates of soil moisture (SM) to a depth of 2 m, snow water equivalent (SWE) and the so-called canopy water (CA), the final parameter being associated with plant-based water content; these estimates are provided in units of kg/m$^3$. The Noah model implicitly assumes water content at a depth greater than 2 m as being "groundwater". As the TWS measured by GRACE is the sum of the various terrestrial components [SM, SWE, CA and groundwater storage (GWS)], simple arithmetic, involving the subtraction of the GLDAS-derived components from the GRACE-derived TWS, permits an estimate of the actual varying groundwater storage, GWS, which is returned in units of cm, as follows:

$$\Delta GWS = \Delta TWS - (\Delta SM + \Delta SWE + \Delta CA) \qquad (1.1)$$

### 1.3.4 Previous GRACE studies of groundwater variations on continental, regional and local scales

Using GRACE data, scientists have been able to reliably monitor monthly GWS changes in the largest of the world's aquifer systems and river basins, including those located in India, Africa and California's Central Valley and the Guarani aquifer in South America. These observations have been invaluable in assessing the status of these critically important groundwater systems in parts of the world where their viability is essential for a significant proportion of the global population. Resolution is, however, the key – both GRACE missions have a spatial resolution of 1°, and, although this has not been a problem for assessing such continental-sized aquifer systems, it is a clear barrier to implementation on regional (and smaller) scales. Indeed, the consensus in the literature is that accurate estimates of groundwater variability necessitate area sizes of approximately 200,000 km$^2$, with a lower limit of 100,000 km$^2$.

Two recent studies attempted to assess the efficacy of using GRACE-derived groundwater estimates on regional scales of less than 100,000 km$^2$. In the first, Biancamaria *et al*. (2019) analysed water mass variations in the Garonne basin of France (drainage area of ~50,000 km$^2$) using both spherical harmonic-derived and mascon-based solutions for inferred TWS, and the SAFRAN and SIM (Safran–Isba–Modcou) hydrological models, both of which are French variants of the GLDAS model infrastructure. These authors also had access to 20 groundwater well gauging stations throughout the region to directly sample the basin and provide a baseline for the hydrological models. Having analysed data from 2002 to 2014, these authors demonstrated good agreement between GRACE and model estimates of TWS anomalies, and highlighted both spatial and temporal resolution as the principal reasons for mismatches between the two. The second study by Rzepecka and Birylo (2020) applied a similar analysis to the Odra and Vistula river basins in Poland, covering 118,900 km$^2$ and 194,500 km$^2$, respectively. Using both the GLDAS-Noah model and data from 215 groundwater wells, they demonstrated a high degree of consistency between the GRACE-derived groundwater variations and data from the wells, with a consistent lag of ~1 month on average; however, there was less consistency when comparing the GLDAS-derived GWS against the same well data.

### 1.3.5 Downscaling strategies for GRACE data

In areas of between 50,000 km$^2$ and 100,000 km$^2$, the utility of GRACE is clearly evident, particularly when it comes to directly associating GRACE-derived water variations with groundwater well levels; however, the evidence is less compelling when comparisons are made with land surface models. The limited resolution of the GRACE data products (1° × 1°) is in stark contrast to the finer resolution possible using the GLDAS and other hydrological land models, which can capture variations below 0.25°. Given a well-sampled set of groundwater wells within the region under scrutiny, and provided that this same region can be considered part of the same hydrogeological context, it is possible to attempt to downscale the GRACE groundwater anomalies to finer resolution. This is a particularly attractive proposition in that it could permit researchers to finely predict groundwater variations in regions lacking well facilities or, conversely, be used to identify those regions that would benefit from the installation of well facilities. A recent demonstration of the capability of using an artificial neural networks approach is provided by the successful downscaling of GRACE gravitational anomalies from ~50,000 km$^2$ to ~16 km$^2$ resolution in California's Central Valley using machine learning models underpinned by (1) groundwater well-level samples, (2) local precipitation and temperature data, (3) local elevation levels and (4) soil surface maps (Miro and Famiglietti, 2018). These authors demonstrated very good correlation coefficients between predicted and measured groundwater levels over a 10-year sampling period and, as a consequence, determined water storage properties at an unprecedented resolution in the Central Valley. Other studies have used a single GRACE tile encompassing solitary aquifers and local precipitation and known abstraction data to track the aquifer status via GRACE data (Gemitzi and Lakshmi, 2017). The important points here are that the downscaling is modelled either by kriging the estimated groundwater measurements on a finer spatial scale than the GRACE data or by directly associating GRACE data with a specific sub-area without kriging. In the latter case, the "standard" methodology of inferring the groundwater signal from the GRACE data by removing the other water components via the use of a land surface model such as GLDAS has been abandoned; in its place, direct measurements of actual groundwater and other potential inputs/outputs (measured precipitation/known abstraction) are used to train algorithms based on either statistical or artificial intelligence (AI) models.

### *1.3.6 Groundwater in an Irish context – implications for this study*

Ireland presents an interesting challenge in the context of the GRACE mission. The island's total surface area is ~84,421 km$^2$ and corresponds to, at best, ~11 1° × 1° "pixels" of GRACE data. The largest river basin, that of the Shannon, encompasses a region of ~17,000 km$^2$, with the remaining river basins < 3000 km$^2$. It is an island, with clear overlaps with coastal waters where tidal signals would be expected to contribute to the varying gravitational anomalies measured by GRACE. From a hydrogeological perspective, only ~5% of the land area hosts sand and gravel aquifers, the rest being bedrock aquifers (Williams and Lee, 2008). Figure 1.1 shows maps of the locations of both aquifer types and their estimated recharge properties. The

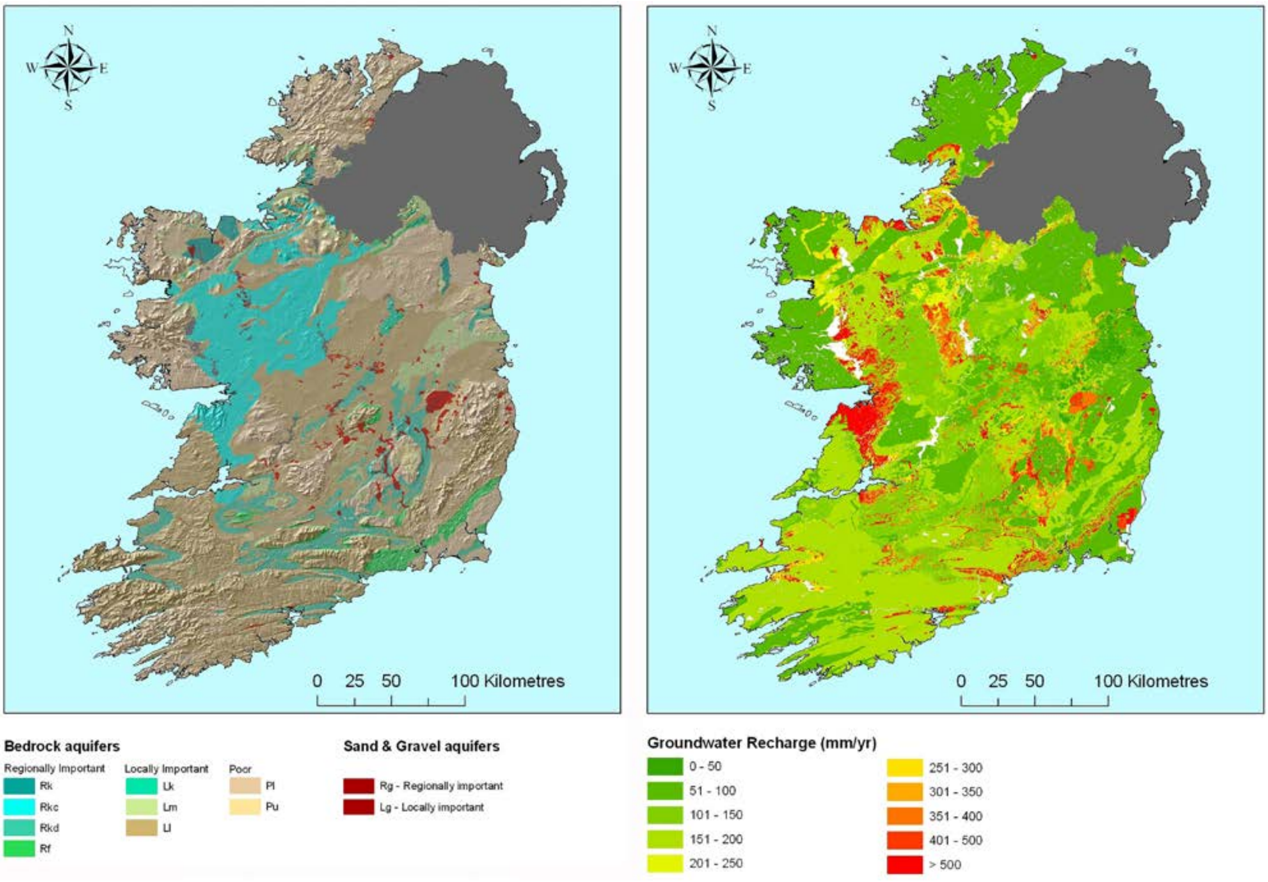

**Figure 1.1. Maps of (left) bedrock and gravel aquifers (GSI) and (right) interim groundwater recharge rates. Adapted from Williams and Lee (2008). Reproduction licensed under Creative Commons Attribution CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).**

map scale conveniently defines the dimensions of a GRACE pixel (~110 km × 70 km at latitude 52°N). The bedrock aquifers are classified as “regionally important” [karstified bedrock (Rk), fissured bedrock (Rf)], “locally important” [bedrock that is generally moderately productive (Lm), bedrock that is karstified to a limited degree or limited area (Lk), bedrock that is moderately productive only in local zones (Ll)] or “poor” [bedrock that is generally unproductive except for local zones (Pl), bedrock that is generally unproductive (Pu)]. The eastern region, encompassing the metropolitan Dublin area along with important agricultural regions, is particularly relevant in that they correspond to regions possessing moderately productive aquifer sources with poor recharging rates (< 100 mm/year), a category that makes up a not insignificant fraction of Ireland’s land area. That being said, the relative complexity of the groundwater composition on spatial scales much lower than those sampled by the available GRACE data products is quite evident, in contrast to the more homogeneous environments associated with the continental-scale river basins and associated aquifers that have been the focus of the majority of published studies using the GRACE mission data. Just as relevant is whether or not any significant perturbations associated with stress events would actually be distinguishable against a “saturated” groundwater background in Ireland, in contrast to other geographical regions with more extreme groundwater conditions.

The key issues to resolve in this case study are the following:

- Is it possible to determine groundwater variations from GRACE data that correlate with data from the existing groundwater well network?
- Is the conventional means of inferring groundwater variations using land surface models in conjunction with GRACE data, as used for ≥ 100,000 $\text{km}^2$ of river basin/aquifer regions, meaningful in an Irish context?
- Is it possible to discern trends in groundwater variation over the timescale of the GRACE mission that could be associated with enhanced abstraction and/or climate change?

In the following chapters, we introduce the data and methodologies adopted to answer these questions, then describe the specific analyses performed to resolve these issues.

# 2 Data and Methodologies

The main objective of this study, as outlined in Chapter 1, is to assess the extent to which satellite data can be used to estimate changes in groundwater in Ireland on useful spatial and temporal scales. To address this, the analysis conducted here, for the most part, necessarily focuses on whether or not the estimates of groundwater changes calculated from satellite data are in good agreement with point measurements from groundwater monitoring wells. This kind of analysis largely amounts to a comparison of the groundwater estimates from satellite measurements with well measurements, with an emphasis on the temporal coherence of any seasonal variation and a correlation of the magnitude of the values obtained from the two different measurement methods.

The GRACE satellite LWE thickness data do not, by themselves, provide a direct measurement of groundwater changes over time; rather they must be processed and combined with other datasets to extract a groundwater signal. Measurements from the EPA HydroNet well network yield a more direct measurement of groundwater and are tabulated as a time series of absolute well depth (depth to groundwater level or depth of the unsaturated zone) relative to Malin ordnance datum (OD). Assembling two comparable datasets, satellite and well measurements, requires the combination of data from the satellites with land model estimates of surface water (non-groundwater), which can then be compared with the values measured for the well network. The three datasets used to achieve this are:

1. GRACE and GRACE-FO satellite data;
2. GLDAS land model data;
3. EPA HydroNet well monitoring network data.[4]

A short description of each of these datasets is given here, with an overview of spatial and temporal distribution and typical ranges of values.

## 2.1 GRACE and GRACE-FO Datasets

Data from the GRACE and GRACE-FO missions are freely available in many formats and stages of data inversion and correction. The fundamental measurements recorded are very precise measurements (differences of ~$10^{-6}$ m in the average separation distance of approximately 200 km) of the instantaneous distance between the two satellites and their precise positions as determined by the global positioning system (GPS). These measurements comprise the L1 datasets and are not generally released. The first stage of data inversion produces the L2 data, which are the geopotential fields in the form of spherical harmonic solutions, and this dataset is available to interested researchers. L3 data are the most processed datasets and are broadly split into land mass data and ocean data. Monthly land mass grids of land water storage and monthly values of ocean bottom pressure are available at a resolution of 1° of latitude and longitude. These L3 data are derived from the L2 spherical harmonic solutions, and a number of corrections must be applied before use in groundwater estimates and analyses.

In addition to the L2 spherical harmonic solutions and the derived L3 mass anomaly datasets, a second data inversion approach produces an independent dataset comprising spherical cap mascon values. These values are represented on a 0.5° latitude–longitude grid, although they represent 3° × 3° equal area caps. For most applications, the mascon dataset is preferable, as it does not suffer from some of the processing artefacts present in the spherical harmonic datasets. A full description of all of the GRACE datasets is given in Swenson and Wahr (2006) and Landerer and Swenson (2012).

As previously stated, these datasets are all calculated independently by the three collaborating institutes,

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[4] The EPA HydroNet well monitoring data were used in the first instance owing to their longer temporal baseline and relative ease of access via https://www.epa.ie/hydronet (accessed 15 March 2021).

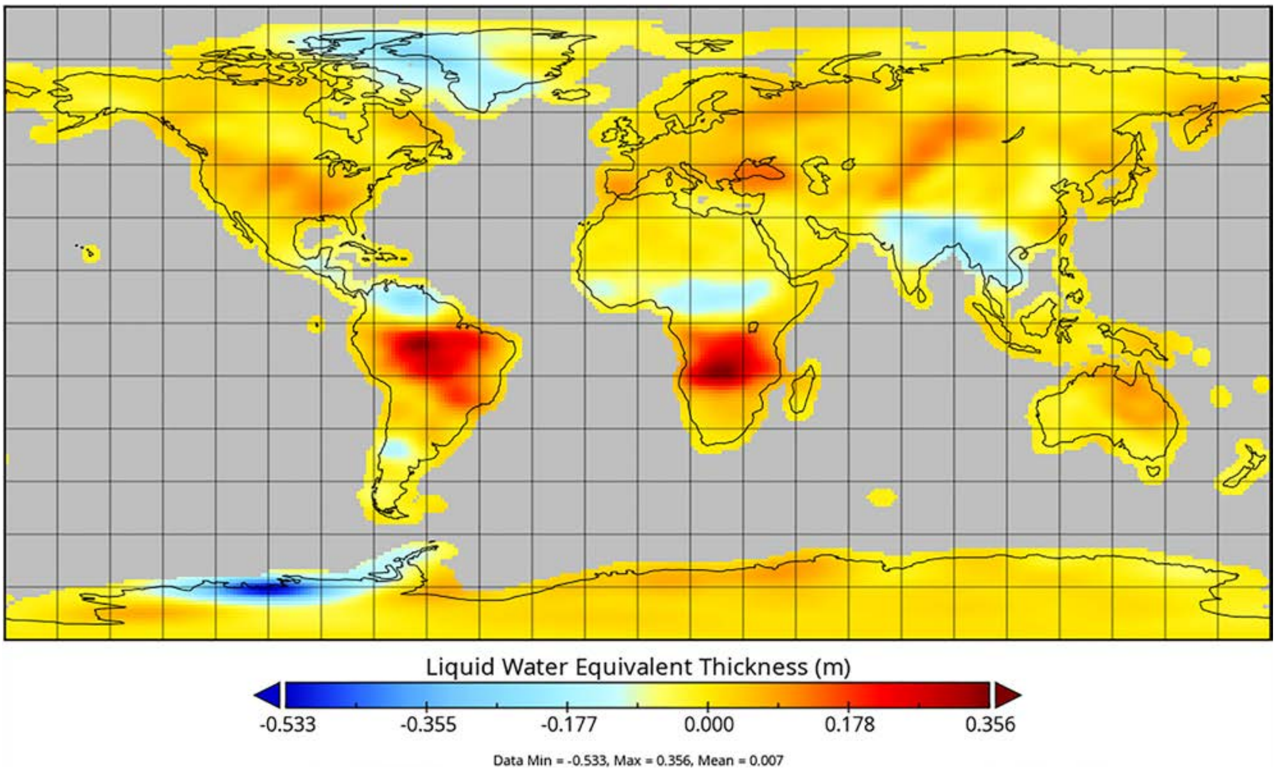

**Figure 2.1. Liquid water equivalent thickness anomalies (m) as measured by the GRACE satellites over the entire globe for April 2010. The increases in groundwater expected at this time of year in the Amazon and in the Congo/Zambesi river basins are apparent. In contrast, groundwater loss in northern India is notable, as are the losses of ice mass in Greenland and, in particular, in the West Antarctic Ice Sheet.**

JPL, CSR and GSFC. Although the resulting data are expected to be largely similar, if not identical, different researchers may have particular reasons for choosing a particular dataset, while some studies have used an average of all three datasets. The GRACE datasets are available as network common data form (netCDF) and American Standard Code for Information Interchange (ASCII) files from the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC) data repository.[5] For this study, the netCDF format files were downloaded and archived locally for further processing and analysis.

Figures 2.1 to 2.4 illustrate the typical range of GRACE TWS anomaly values, represented as LWE thickness values, which are referenced against the long-term mean range between 2002 and 2018. The maps show the monthly values for April 2010 over the entire globe, over the European land mass, over the UK and Ireland, and over Ireland only, and illustrate that the range of variation in the values over Ireland is much less than the range of variation over the entire globe, the difference being approximately two orders of magnitude.

Figure 2.1 shows a typical snapshot (April 2010) of the variability in the GRACE LWE values over the entire Earth land mass. The resolution is 1° latitude–longitude shown on a 15° grid and the units are metres. The variations over this epoch range from a minimum of approximately –0.5 m to a maximum of about 0.4 m. Continental-scale river basin aquifers are clearly seen to be charging in South America and Africa, as happens annually around this time. Apparent losses proximal to these regions are part of this seasonal cycle. However, LWE losses evident in Antarctica and along the western Greenland ice sheet are associated with significant ice loss due to global warming, and those in northern India are a consequence of unsustainable abstraction activity in the subcontinent.

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[5] https://podaac.jpl.nasa.gov/ (accessed 15 March 2021).

Figure 2.2 shows a map of the GRACE LWE values over Europe for April 2010. By comparing this with the map shown in Figure 2.1, it is clear that the variations from the mean over this region are less than over the entire globe, falling between lower and upper bounds of about –0.1 m and 0.2 m. On this scale, there is no observable difference in the values for the pixels over Ireland or the UK. The increased LWE signal over the Black Sea is consistent with the increased run-off into this estuarine-type basin known to occur at this time of the year.

Reducing the mapped area further to focus on Ireland and the UK land masses also reduces the scale of the variability in anomalies from the mean GRACE LWE, and the range is now between about –0.02 m and 0.04 m, as illustrated in Figure 2.3. Even on this much smaller scale, there is still relatively little variation over the entire Irish land mass and only very small variation over the UK pixels.

When the mapped area is reduced still further to include only the Irish land mass (Figure 2.4), the variability in the anomalies from the mean of the GRACE LWE are easily contained within the range from about –6 cm to 6 cm, approximately two orders of magnitude less than the variability seen over the entire Earth land mass shown in Figure 2.1.

At first glance, it seems obvious that, while the GRACE satellite measurements can certainly resolve large-scale features (e.g. large mountain ranges, tropical rainforests, polar ice sheets) over the entire land mass area of the Earth, it is perhaps less obvious that they are sufficiently sensitive to usefully detect small-scale detail over an area the size of Ireland, which is covered almost completely by about 11 1° pixels, among which the variation is typically less than about ±6 cm. It further suggests that attempting to use these data to resolve small changes in groundwater over river basin scales will be a much more significant challenge.

As described above, GRACE data are also available as mascon data, and these data are plotted in Figure 2.5 for April 2010. Over the entire globe, these values show much greater variability than the land mass grids shown in Figure 2.1, with a minimum value of about –377 cm and a maximum of about 209 cm. The data are plotted here on a scale from –210 cm to 210 cm, so that the large-scale features can be seen and a similar pattern to that shown in Figure 2.1

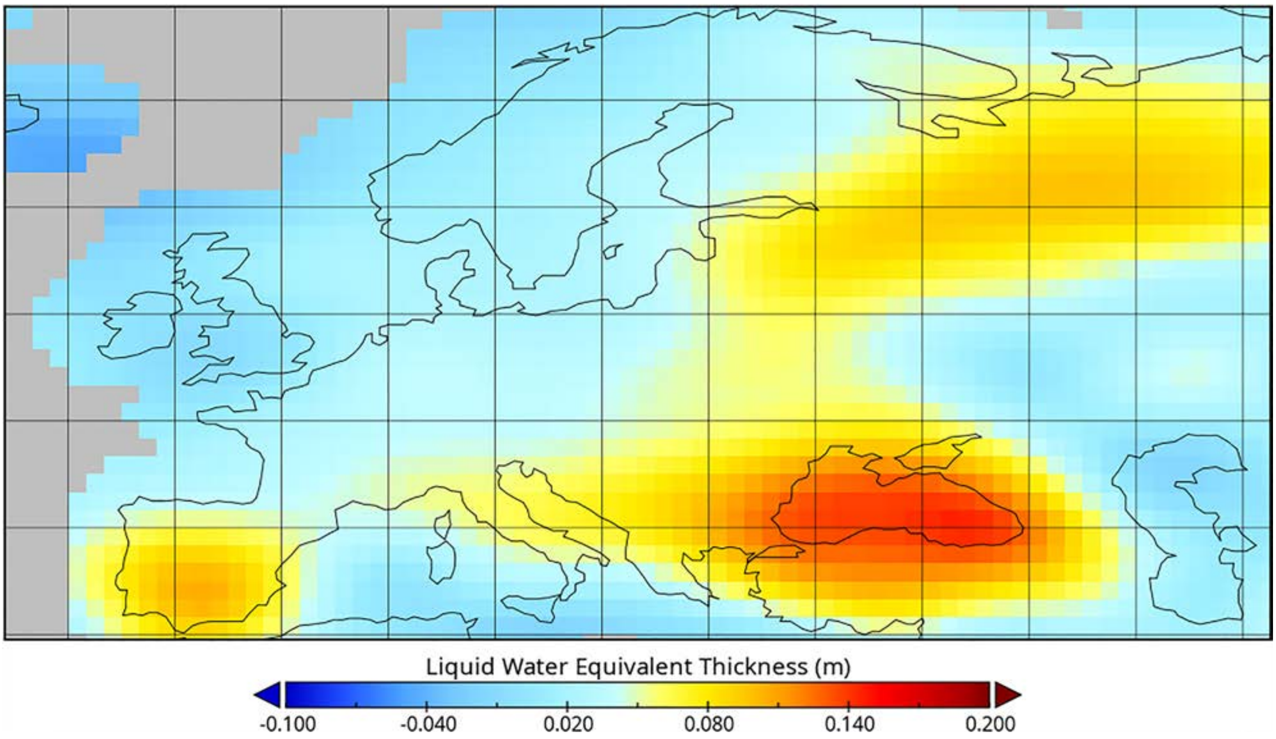

**Figure 2.2. Liquid water equivalent thickness anomalies (m) as measured by the GRACE satellites over Europe for April 2010.**

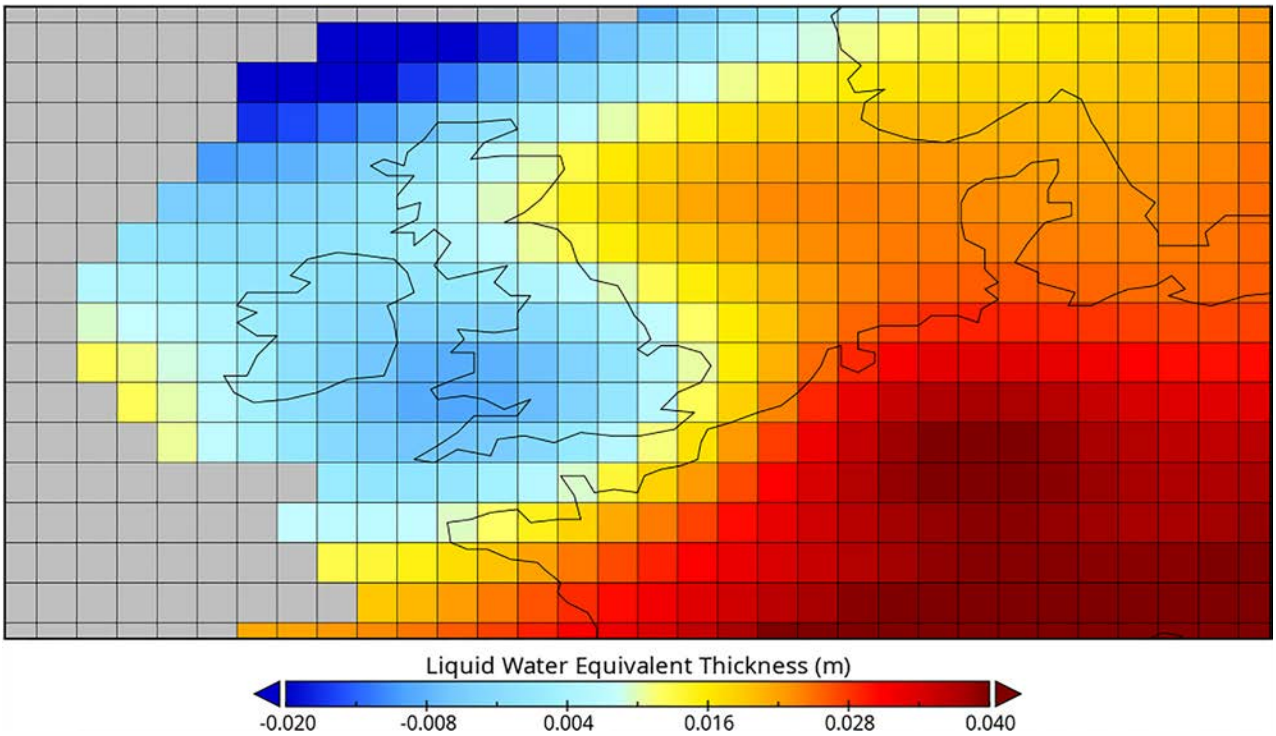

**Figure 2.3. Liquid water equivalent thickness anomalies (m) as measured by the GRACE satellites over Ireland and the UK for April 2010.**

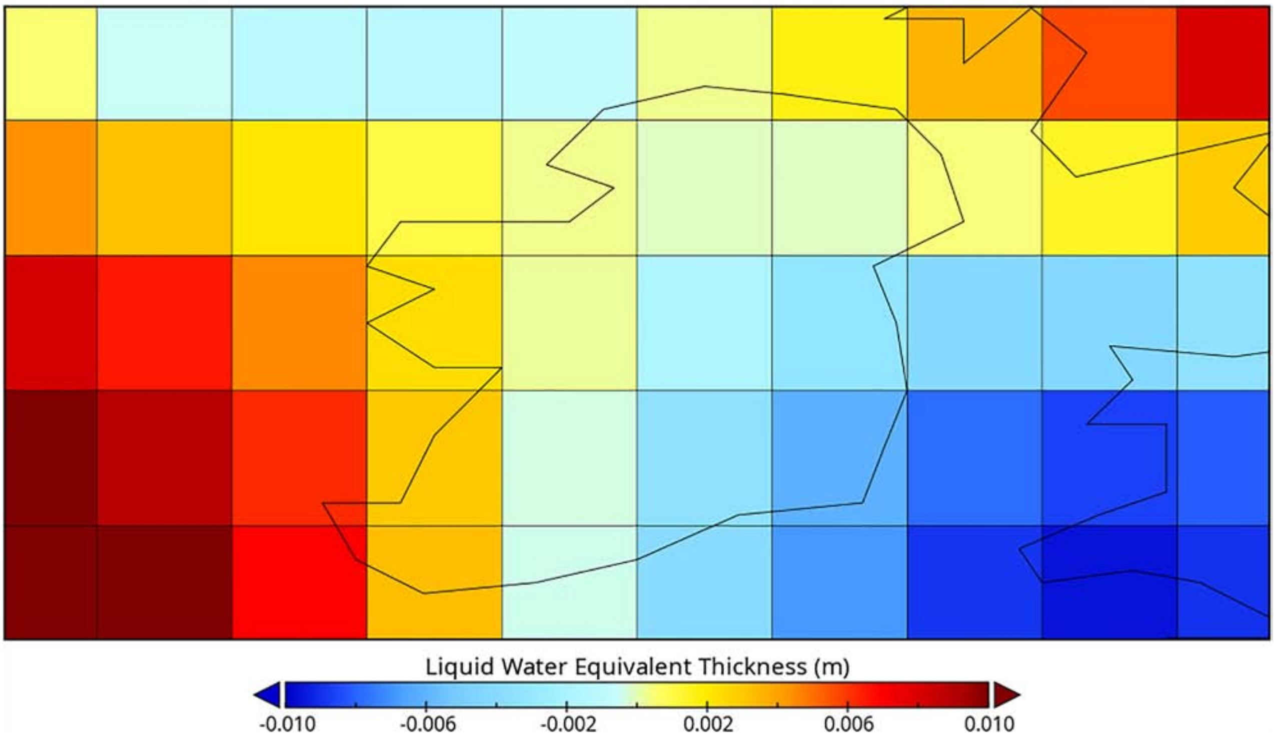

**Figure 2.4. Liquid water equivalent thickness anomalies (m) as measured by the GRACE satellites over Ireland for April 2010.**

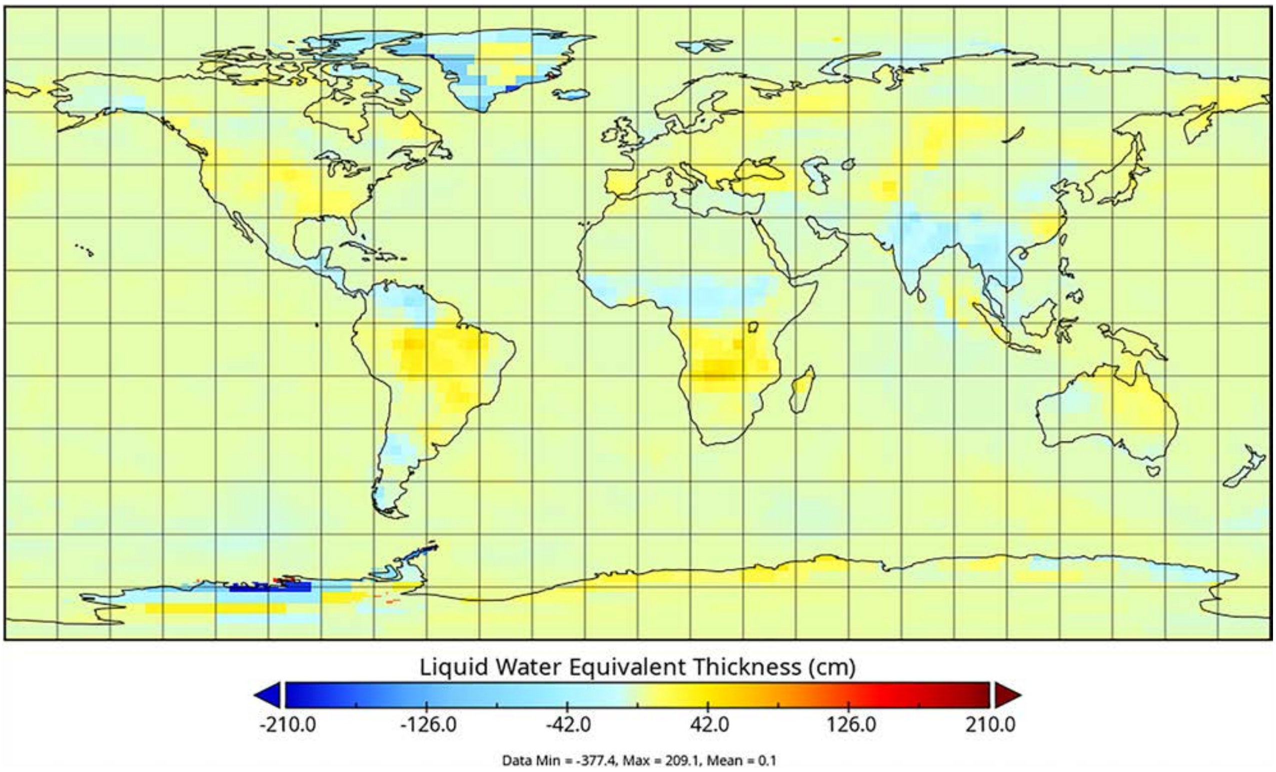

**Figure 2.5. GRACE liquid water equivalent 3° mascon values over the entire globe mapped on a 15° grid for April 2010. Although the values are plotted at a resolution of 0.5°, each value represents a spherical cap mascon of 3° in size.**

is obvious, with relatively large values over tropical regions and smaller values over some of the larger mountain ranges and in the polar regions. These data provide a more nuanced interpretation of the gravitational anomalies detected by GRACE, particularly around Greenland and Antarctica.

Similar to the land mass grids plotted in Figures 2.1 to 2.4, as the map area decreases from covering the entire globe to Ireland, the scale of variability of the values contracts over about two orders of magnitude. Figure 2.6 shows the mascon values over Ireland for April 2010 and illustrates that there is almost no variation in the values over the Irish land mass for this particular month, a feature present in most of the monthly maps of GRACE mascon values over Ireland.

## 2.2 GLDAS Datasets

The GRACE L3 data provide gravitational mass anomalies, which include contributions from mass changes due to all sources including, but not limited to, groundwater. For example, over land, this includes movement of magma fields, changes in crustal characteristics such as polar ice sheet mass changes and contributions due to surface water such as SM, water stored in vegetation and water stored in snow. Although most of the changes in mass detected by GRACE can be attributed to total terrestrial water changes, accurate estimates of groundwater changes require that the gravitational signal due to water changes in the higher layers be subtracted from the total signal. This calculation requires accurate estimates of the water stored in the non-groundwater strata. The GLDAS land models provide such estimates, and the use of these datasets for this purpose has become an almost standard approach in recent studies. The GLDAS model system is composed of four subsidiary models; a full description of the model is given in Rodell *et al*. (2004). In this desk study, data from the Noah model were used, as this is the only model that produces data at both 1° and 0.25° resolutions.

Data are available as netCDF, ASCII and, in some cases, gridded binary (GRIB) format files from the NASA Earth Observing System Data and Information System (EOSDIS) Earthdata data repository; the netCDF format files were downloaded and archived locally for use in this study.

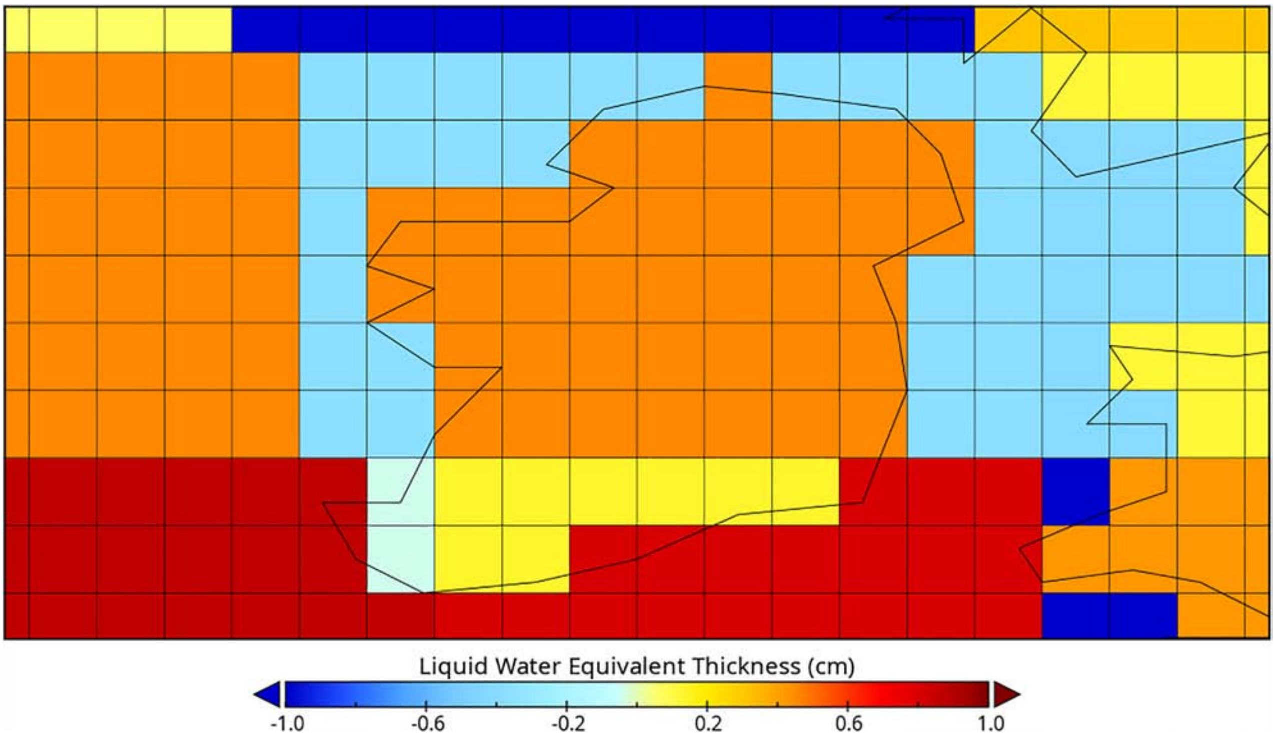

**Figure 2.6. GRACE liquid water equivalent 3° mascon values over Ireland mapped on a 0.5° grid for April 2010. Although the values are plotted at a resolution of 0.5°, each value represents a spherical cap mascon of 3° in size.**

The GLDAS-Noah land model produces data products at resolutions of 1° and 0.25° latitude–longitude. As already described, an almost standard approach has been widely adopted by most researchers to the calculation of groundwater using GRACE and GLDAS-Noah datasets, and this convention has also been followed in this study. To facilitate this, in March 2020 JPL released a version of the GLDAS-Noah dataset that aligns temporally with the GRACE dataset and provides values of variations from the long-term mean of TWS, including SM, CA and SWE at a spatial resolution of 1° latitude–longitude. Figure 2.7 shows a map of these values over the whole Earth land mass at a resolution of 1° on a 15° grid for April 2010 in units of mm. On this scale and at this resolution, comparison with the GRACE data plotted in Figures 2.1 and 2.5 shows that a broadly similar general pattern of large-scale features is present in all three maps. The range of values of variation in TWS over the whole Earth for this period is from a minimum of about –490 mm to a maximum of about 620 mm. On this scale, there is no appreciable variation visible in the values over Ireland.

When the scale of the map is reduced to the general area of the European land mass, the scale of the variations in TWS decreases accordingly; the range of values is now bounded by a minimum of about –40 mm and a maximum of about 200 mm, as illustrated in the map in Figure 2.8. Some comparatively small variation is now visible in the pixels over Ireland.

Reducing the area of the map to the size of the Irish land mass highlights a reduction of about an order of magnitude in the scale of the variations in modelled TWS to within ± 20 mm over the approximately 11 1° pixels that cover almost the whole country (Figure 2.9).

For this work, it was difficult to discern a conclusive consensus regarding which version of the GRACE data would yield the best results for Ireland, either from the literature or from direct discussions with other researchers. Researchers at JPL, who produce these datasets, recommended that this study should use mascon data because these data do not suffer from the kinds of striping and aliasing artefacts that may be present in the land mass grids calculated from the spherical harmonics L2 data. However, even though the mascon data are provided on a 0.5° grid, each value represents a 3° spherical cap mascon, meaning that there is considerable cross leakage between

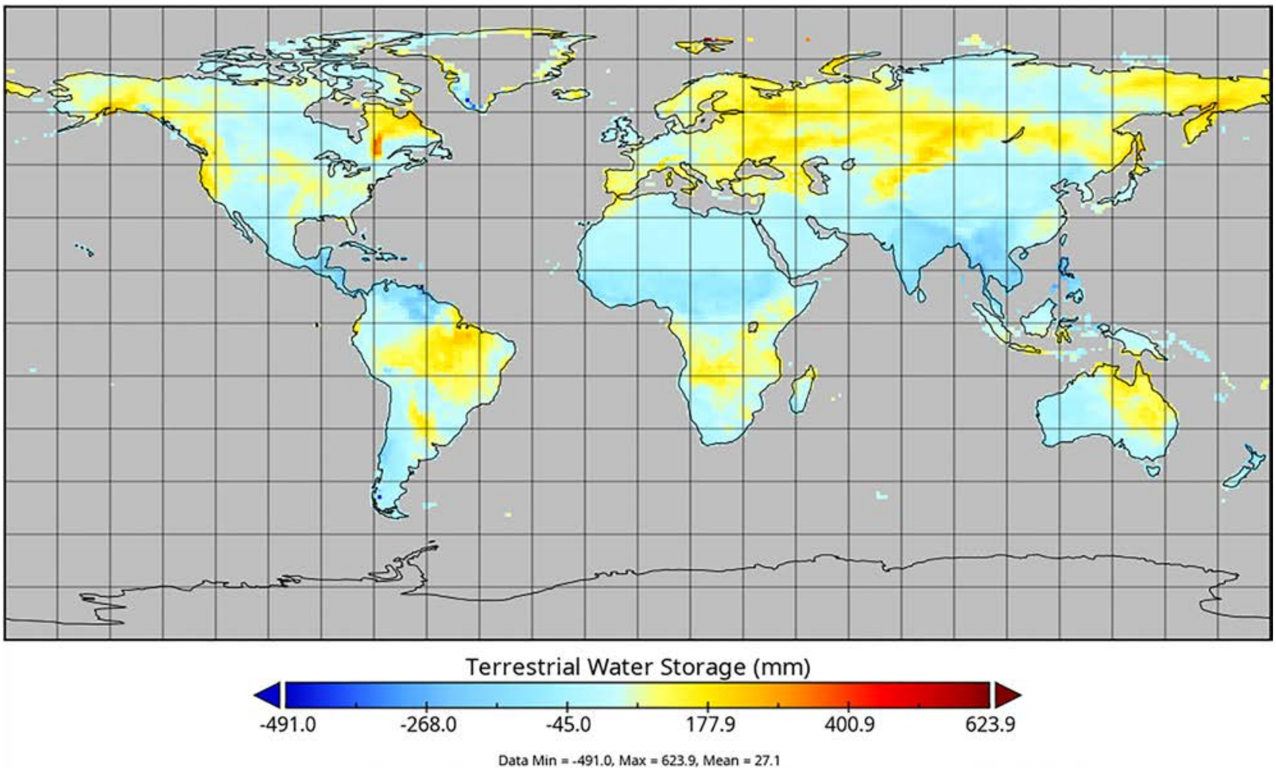

**Figure 2.7. Values of variations in terrestrial water storage (mm) from the long-term mean from the GLDAS-Noah land model at a resolution of 1° on a 15° grid over the entire globe for April 2010.**

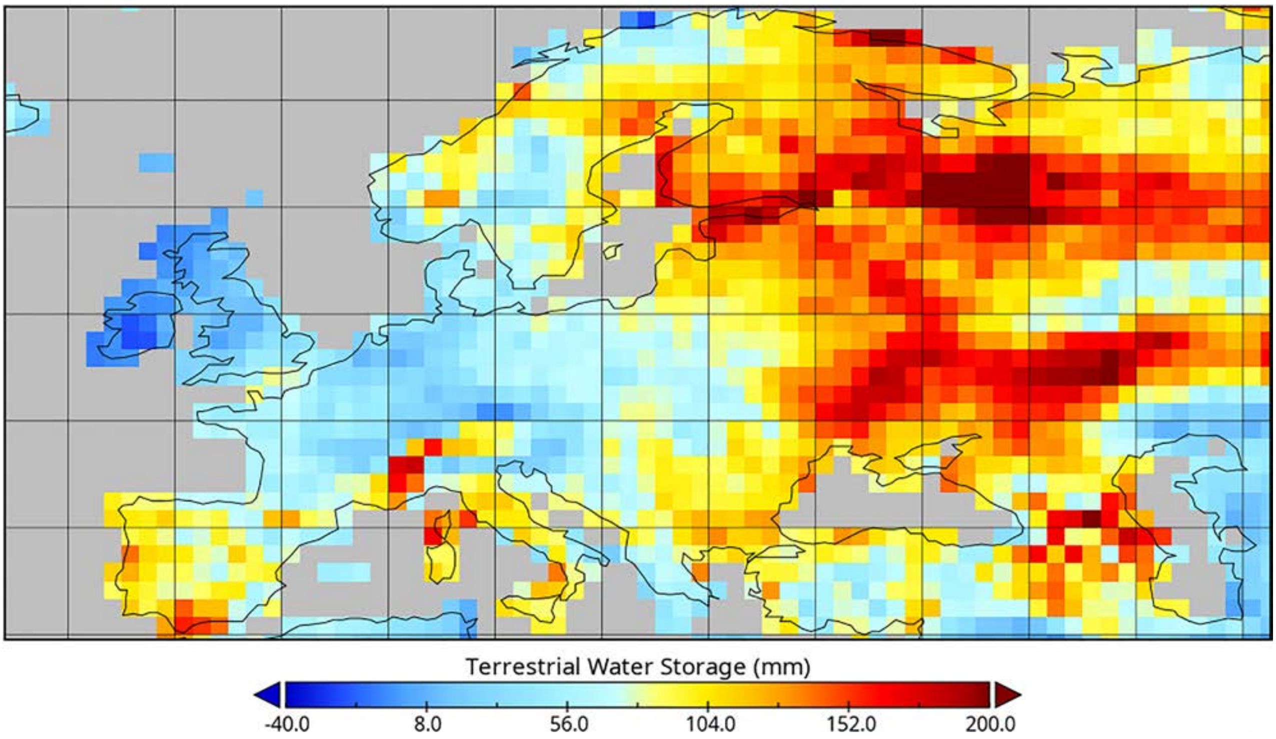

**Figure 2.8. Values of variations in terrestrial water storage (mm) from the long-term mean from the GLDAS-Noah land model at a resolution of 1° on a 6° grid over Europe for April 2010.**

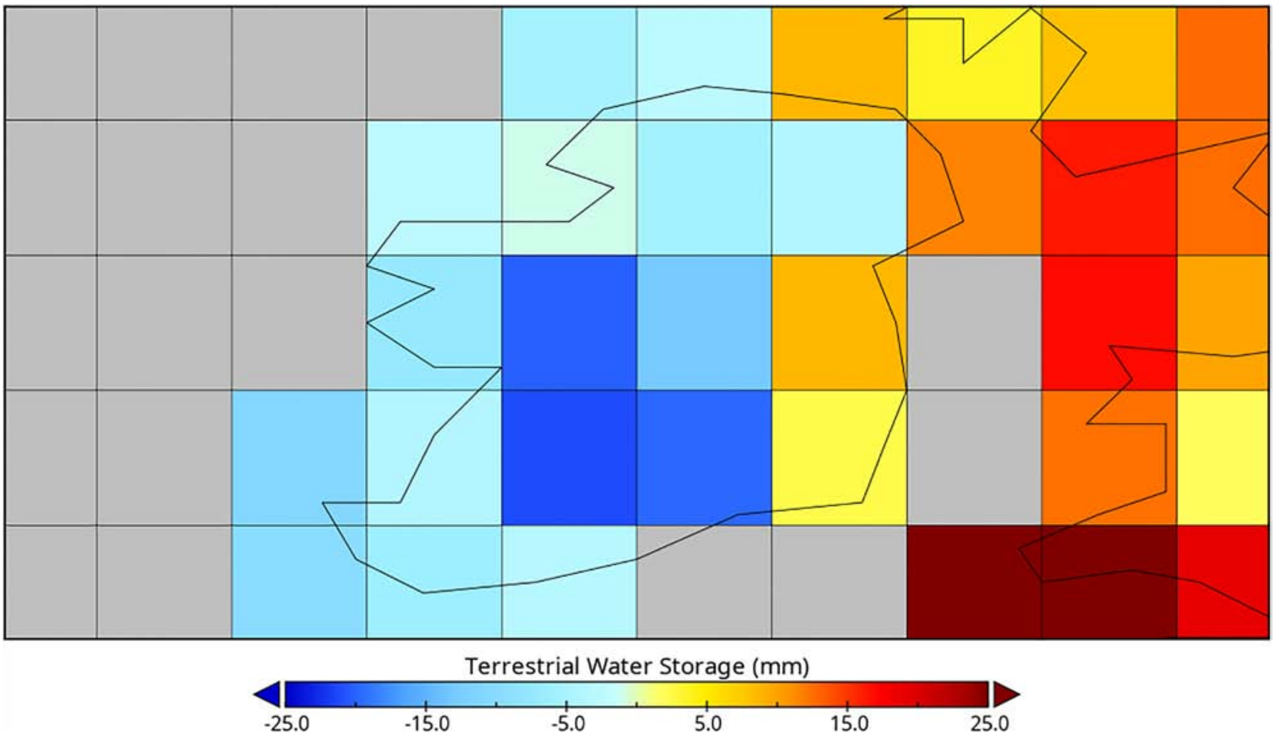

**Figure 2.9. Values of variations in terrestrial water storage (mm) from the long-term mean from the GLDAS-Noah land model at a resolution of 1° on a 1° grid over Ireland for April 2010.**

adjacent values. Although this may not be a critical issue over large spatial scales, it may influence results to a much greater extent over an area the size of the Irish land mass. For this reason, both datasets were downloaded and used in this study.

## 2.3 EPA HydroNet Monitoring Well Network Datasets

The EPA HydroNet network[6] is a national network of 360 monitoring wells, of which 235 are currently inactive, leaving a total of 125 active wells distributed throughout the country. The locations of all wells are shown in Figure 2.10. Groundwater-level data collected from EPA and local authority hydrometric stations are processed and archived by the EPA and are available for download from the EPA HydroNet website. Records of groundwater-level data at some of these locations stretch back to the 1970s, and levels were measured using either manual dip methods or automated sensors. Records for most of the 125 currently operational automated wells began during 2009, with a small number starting in late 2008. To include the maximum number of wells in this study, data from December 2009 to July 2017 were included in the study, with a final number of 110 active wells. Groundwater levels in these active wells are recorded automatically at 15-minute intervals and these data are processed by the EPA and archived on the EPA HydroNet website. Daily averaged time series from individual wells can be viewed on the website, or a single data file, in comma-separated value (CSV) format, corresponding to a particular well can be downloaded. In addition to the well depth data, each file also contains information such as the name of the well, the location in eastings and northings format and the station number. The files for all 110 active wells used in this study were downloaded individually and archived locally for further analysis.

For comparison with the GRACE and GLDAS datasets, the location of each well was converted to latitude and longitude, monthly averages were calculated and the data from all 110 active wells were included in a single data file. The variance from the long-term mean (December 2009 to July 2017) for each well was also calculated and these values were used in all subsequent analysis. The GRACE

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[6] http://www.epa.ie/hydronet/ (accessed 15 March 2021).

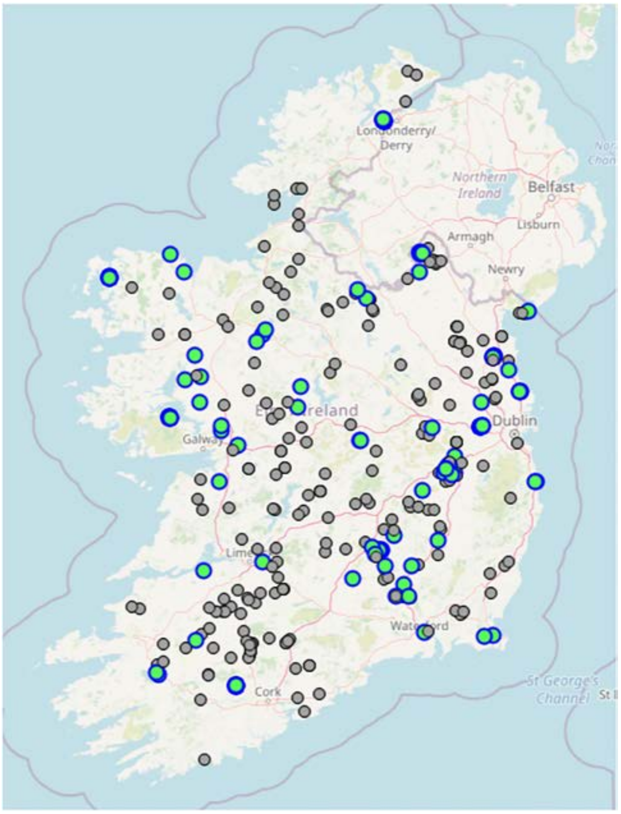

**Figure 2.10. Map showing the locations of the 360 wells that form part of the EPA HydroNet monitoring well network. Active wells (*n* = 125) are represented as green and blue circles and inactive wells (*n* = 235) as grey circles.**

data record runs from April 2002 to July 2017, so the overlap between well data and GRACE data is a period of about 74 months.

## 2.4 Computational Methods and Data Management

All of the computational work for this project was carried out in the open-source Python (version 3.8) programming language using the Spyder Integrated Development Environment (IDE) on a Ubuntu Linux platform. This software development environment is one of the most commonly used for modern data science analysis and particularly for scientific applications such as this. Many high-level third-party application programming interfaces (APIs) and libraries have been developed for specific purposes and many of these were used extensively in the code developed here. For example, NumPy, SciPy and pandas are three of the most common Python libraries that implement efficient data array and data frame manipulation tools; matplotlib was used to create most of the plots; cartopy is a mapping library and was used to create many of the maps; and PyKrige is a Python library that implements kriging. In common with most open-source software, most of these libraries, and indeed the Python language itself, are under constant development, with new features being added regularly and frequently.

All data for this work were locally archived for use with the Python scripts developed. In the cases of the GRACE and GLDAS datasets, this is a relatively straightforward process; the GRACE data repository is accessed by mounting it as a distributed authoring and versioning file system (davfs) drive, and any files required are simply copied, whereas the GLDAS data can be selected through a web interface, which generates a list of files that can then be downloaded by means of GNU Wget. Both of these datasets are available in netCDF format, and the Python netCDF4 library was used to interrogate the files and extract the required arrays of data. The EPA HydroNet data can be accessed on the HydroNet website, but the process of downloading the data is more time-consuming, because the data files must be downloaded for each well individually as a zip archive that also contains a CSV file. The file headers contain some information about the well, including its location in eastings and northings format. For comparison with the GRACE and GLDAS datasets, the location had to be converted to longitude and latitude and all of the individual well data files amalgamated into one array covering the Irish land mass. A considerable improvement for future work would be to provide access to this data in a similar manner to that used to access the GRACE or GLDAS datasets, either where the full datasets can be downloaded as a single file or where all files can be downloaded together. In any case, the efficient assimilation of this dataset on an operational basis into a future model will require the development of a suitable API or data import interface.

# 3 Analysis and Results

The principal objective of this study is to assess the feasibility of using GRACE measurements to determine groundwater variations at useful spatial resolution over Ireland. The approach to this adopted in most other current studies is the now almost standard method of using a combination of GRACE measurements and suitable land model measurements to isolate groundwater variations and then comparing these values with ground truth measurements, usually well measurements. The key differences between this study and other published studies are (1) the size of the land mass, Ireland being much smaller than the land masses considered in these other studies; and (2) the nature of the underlying geomorphology and soil cover, Ireland being relatively inhomogeneous. Both of these considerations led to the requirement for higher spatial resolution of the three different datasets to attempt to obtain a sufficiently detailed map of the groundwater characteristics. The main focus of the analysis here is therefore to assess if this common approach to inferring groundwater variations using land surface models in conjunction with GRACE data, as used for ≥100,000 km$^2$ river basin/aquifer regions, can yield useful results for a region the size of Ireland, with its detailed variations in geological structure over relatively fine spatial scales.

The limiting factor in this respect is the resolution of the GRACE data. The land mass grids derived from the spherical harmonic solutions have a resolution of 1° × 1° latitude–longitude, while the mascon values are provided on a 0.5° grid, although each value represents a 3° mascon. The entire land mass of Ireland is almost completely covered by 11 such 1° pixels, and both GRACE and GLDAS data are available at this resolution. However, the Noah sub-model from the GLDAS system also provides data and 0.25° resolution, which allows the possibility of developing a downscaling scheme to determine groundwater variations at this increased resolution. In the analysis developed here, we first present the results obtained from using data at 1° resolution and then explore whether this could be improved using the higher resolution GRACE mascon data.

Although a spatial resolution of 1° latitude–longitude is, by itself, not adequate to resolve the features of smaller basin-scale groundwater changes, particularly over Ireland where the underlying geomorphology is highly variable over much smaller spatial scales, a high degree of variability among the Irish GRACE pixels would at least indicate that the satellite measurements are sensitive to different groundwater characteristics over different regions of the country. This kind of variability is not clearly evident in the GRACE data, as shown in Figure 2.4, which shows not only that the variability across the Irish pixels is very small compared with global variability (approximately two orders of magnitude less), but also that there appears to be a very uniform east–west trend, and this seems to be part of the much larger scale features seen in Figure 2.3. This is even more pronounced in the GRACE mascon data plotted in Figure 2.6: although the spatial resolution appears to be higher because the mascon values are reported on a 0.5° latitude–longitude grid, there is almost no variation in the magnitude of the values over the entire island. However, notwithstanding this relatively large-scale coarse-resolution view afforded by the 1° GRACE and GLDAS data, the analysis presented here shows that the regular annual seasonal patterns in both of these datasets consistently track a similar pattern in the measured well data. Although all three signals are generally consistent over the whole study period, the later part of the period (from about 2014 onwards) exhibits a possible phase shift, particularly between the GRACE and well signals.

## 3.1 One-degree Resolution

The 1° pixels covering most of the Irish land mass roughly form a grid of three rows and four columns, and, for the purposes of this part of the analysis, this grid was labelled with coordinates, with (0,0) being the bottom left corner and (2,3) the top right corner, as illustrated in Figure 3.1. The locations of the active EPA HydroNet wells are also plotted on the map in Figure 3.1 and it is clear that, although some pixels

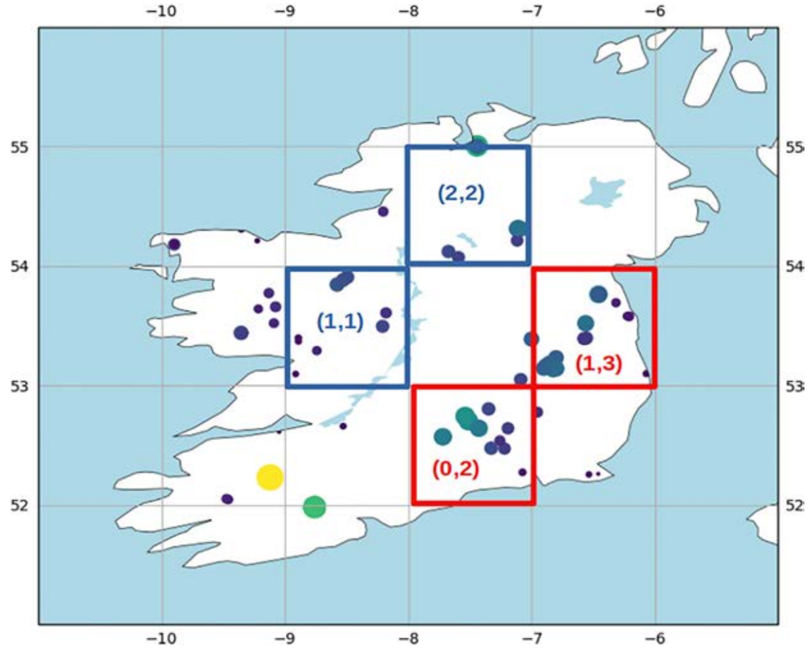

**Figure 3.1. Map of Ireland using a equirectangular projected 1° latitude–longitude grid showing well locations and measured groundwater depth for April 2010 and the pixels selected for case study. The colour and size of each well point represents the well depth for this particular time snapshot: the greater the size and the lighter the colour, the greater the depth.**

include quite a few wells, others have very few or none at all. Four pixels that contained a number of wells were selected for closer study and these four pixels are further divided into two types, roughly based on the number of wells within each pixel; the pixels outlined in red, (0,2) and (1,3), have more wells than those outlined in blue, (1,1) and (2,2). Somewhat conveniently, this division also coincides very generally with two areas of different underlying bedrock and different types of aquifers, as illustrated in Figure 1.1. Table 3.1 summarises the locations and underlying aquifer types for each of the selected pixels.

For comparison with the 1° GRACE and GLDAS data, the variations in well depth from a long-term mean (using the same date range used to calculate the GRACE and GLDAS long-term mean) were calculated, and 1° pixel measured well values were calculated by averaging the values of all wells located within each individual pixel. The number of wells contributing to the values calculated for each pixel are listed in Table 3.1.

The first step in the analysis was to extract two groundwater signals, one from orbit and one from ground measurements, and look for any possible correlation between them. Values of groundwater as

**Table 3.1. Description of the location and underlying aquifer types for the four selected 1° pixels, and the number of wells within each pixel**

| Pixel location | | Bedrock aquifer type | Number of wells |
|---|---|---|---|
| (1,3) | Includes Dublin, Kildare, Meath, Louth and part of Wicklow | Mostly locally important, moderately productive bedrock | 35 |
| (0,2) | Includes Waterford, Kilkenny and parts of Tipperary and Laois | Mixture of regionally important karst field (diffuse) and locally important moderately productive bedrock | 10 |
| (1,1) | Includes Galway, Roscommon and part of Mayo | Mostly regionally important karst field (conduit) | 9 |
| (2,2) | Includes parts of Cavan, Monaghan, Leitrim, Donegal, Fermanagh, Tyrone and Derry | Mostly generally unproductive bedrock except for local zones | 8 |

measured by GRACE were calculated by subtracting the soil and surface water estimates of the GLDAS model from the total TWS values given by GRACE, and time series of these values (ΔGWS) were plotted with the well data, as shown in Figure 3.2. For all four pixels, there is a reasonably clear and consistent annual seasonal cycle in the groundwater levels represented by the well data, with peak levels occurring in winter (December/January) and minimum levels usually occurring in late summer or autumn, although there is considerable deviation from this regular pattern at certain times in some pixels. It is, however, rather less clear if there is any regular pattern in the groundwater signal calculated from GRACE and GLDAS data, and there is no discernible coherence between the two signals for any pixel over most of the study period.

To examine this further, rather than comparing the calculated groundwater values with the measured well values, the individual GRACE (i.e. TWS) and GLDAS signals were compared with the well signals. The time series over the whole study period for GRACE and well signals, GLDAS and well signals and GRACE and GLDAS signals for the eastern pixel (1,3) are plotted in Figure 3.3.

In contrast to the time series in Figure 3.2, the plots in Figure 3.3 exhibit much greater synchrony between the three pairs of data series plotted. The GRACE signal now appears to track the seasonal cycle of the well measurements to some degree and also to align with the GLDAS signal reasonably well. The best coherence appears to be between the GLDAS model values and the well measurements, which track very closely, particularly over the first part of the period up to about 2014, but appear to be phase shifted over the latter half of the series.

To further examine and quantify any relationships between these pairs of signals, simple linear regression analyses were carried out and Pearson *R* correlation coefficients were calculated. The results of this analysis are plotted in Figure 3.4, which shows scatter plots of the four pairs of parameters compared with fitted lines and Pearson *R* coefficient values. Although none of the *R* values here indicates a particularly strong correlation or provides convincing evidence of an unambiguous

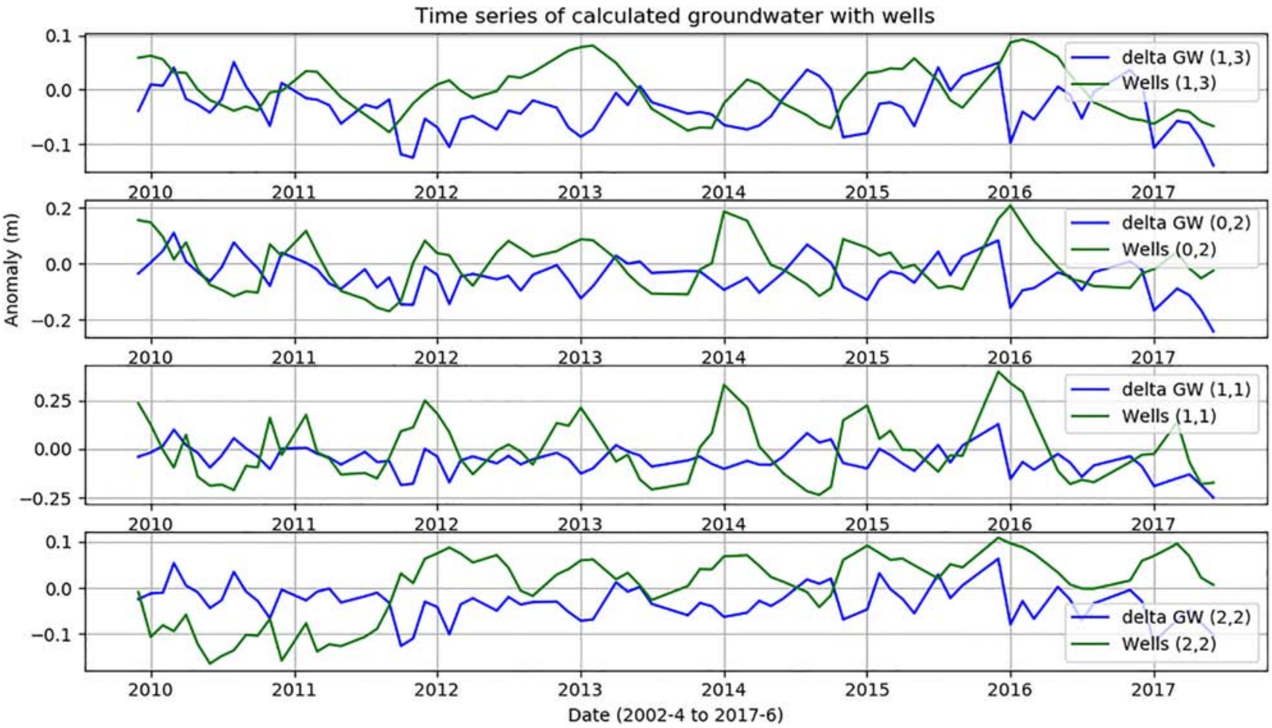

**Figure 3.2. Time series of calculated groundwater anomaly values (ΔGWS, or delta GW here) calculated by removing the GLDAS contribution from the observed GRACE TWS signal, and measured HydroNet well values for each of the four case study pixels. The well values have been reduced by a factor of 10 to scale the amplitude for plotting purposes.**

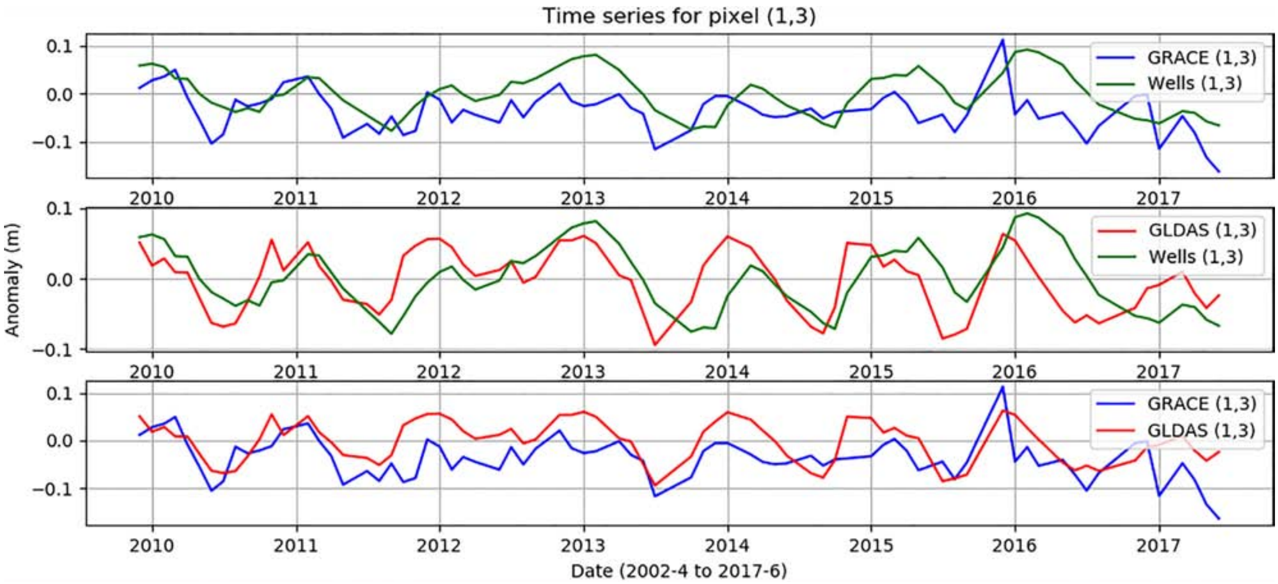

**Figure 3.3. Time series of GRACE, GLDAS and HydroNet well data for pixel (1,3), including Dublin, Kildare, Meath, Louth and part of Wicklow. The well values have been reduced by a factor of 10 to scale the amplitude for plotting purposes.**

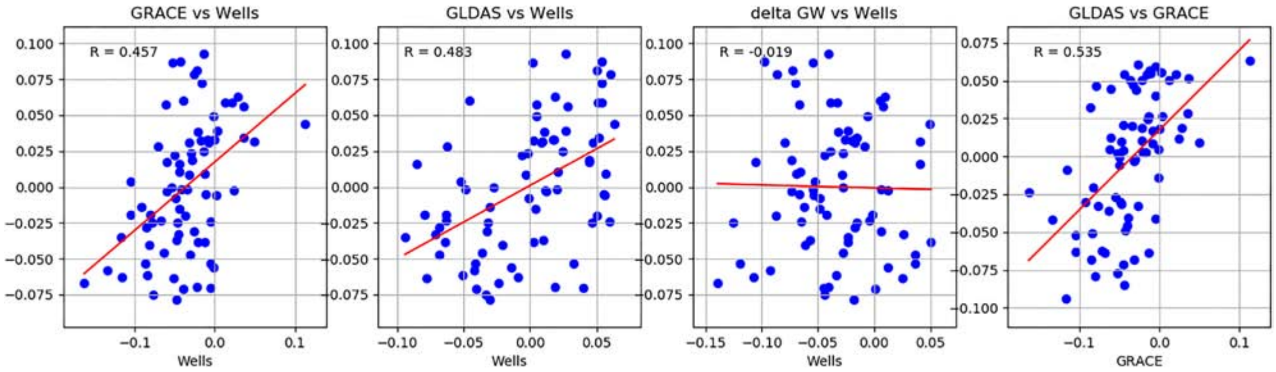

**Figure 3.4. Scatter plots of GRACE, GLDAS, calculated groundwater (delta GW) and HydroNet well data with trend lines fitted using linear regression analysis for pixel (1,3) for the period December 2009 to July 2017.**

determining relationship between GRACE-detected groundwater and well measurements, it is clear that there is a consistent correlation between GRACE and well data, GLDAS and well data, and GRACE and GLDAS data, with *R* values of approximately 0.5 in all cases. Unsurprisingly, and as already indicated by the time series plots in Figure 3.2, this analysis does not show any correlation between the calculated groundwater (ΔGWS) and the well measurements.

A similar analysis was carried out for all four selected pixels, and Figure 3.5 shows plots of the time series for the southern (0,2) pixel, covering Waterford, Kilkenny and parts of Tipperary and Laois. The results are largely similar to the pattern observed for the (1,3) pixel, covering Leinster, with reasonably obvious coherence between the three pairs of parameters plotted. Linear regression analysis produced the results plotted in Figure 3.6, which show some correlation between GRACE and well data ($R \cong 0.5$), and GLDAS and GRACE data ($R \cong 0.5$), but a strong correlation between GLDAS and well data ($R \cong 0.8$). It appears that, in this case, the GLDAS model data capture the variability in the measured well data significantly better than the GRACE signal.

Analysis of the GRACE, GLDAS and well data from the western pixel, (1,1), covering most of Galway and

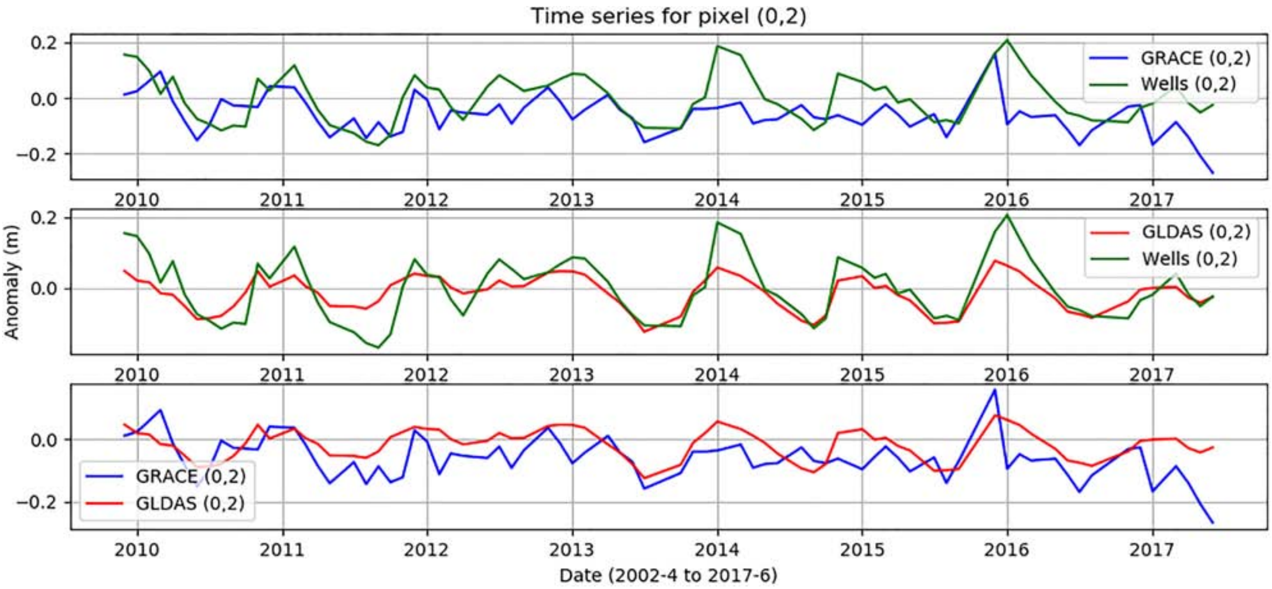

**Figure 3.5. Time series of GRACE, GLDAS and HydroNet well data for pixel (0,2), including Waterford, Kilkenny and parts of Tipperary and Laois. The well values have been reduced by a factor of 10 to scale the amplitude for plotting purposes.**

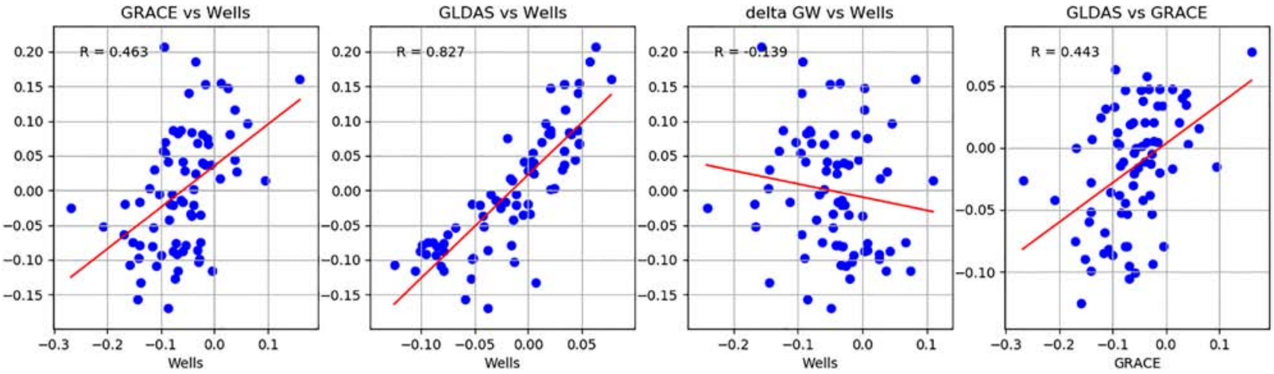

**Figure 3.6. Scatter plots of GRACE, GLDAS, calculated groundwater (delta GW) and HydroNet well data with trend lines fitted using linear regression analysis for pixel (0,2) for the period December 2009 to July 2017.**

Roscommon and part of Mayo, produced a broadly similar pattern to that already seen in the two previous pixels, as shown in the time series plots in Figure 3.7. Analysis of the correlation between the three pairs of parameters yielded roughly similar results, although with slightly lower values of correlation coefficients ($R \cong 0.4$) between the GRACE and well data and the GLDAS and GRACE data than for the other pixels (Figure 3.8). There is, however, a very strong correlation here between the GLDAS data and the well measurements ($R \cong 0.9$). This pattern of correlations is very similar to that seen for pixel (0,2) over Munster, where a similarly high correlation between GLDAS and well measurements was observed. It is perhaps worth noting that both of these pixels, (0,2) and (1,1), have underlying karst field-type aquifers, with some being karst field (diffuse) in the southern (0,2) pixel and almost all being karst field (conduit) in the western (1,1) pixel.

Results for the northern pixel, (2,2), covering parts of Cavan, Monaghan, Leitrim, Donegal, Fermanagh, Tyrone and Derry, were generally different from those obtained for the other three pixels. This pixel extends

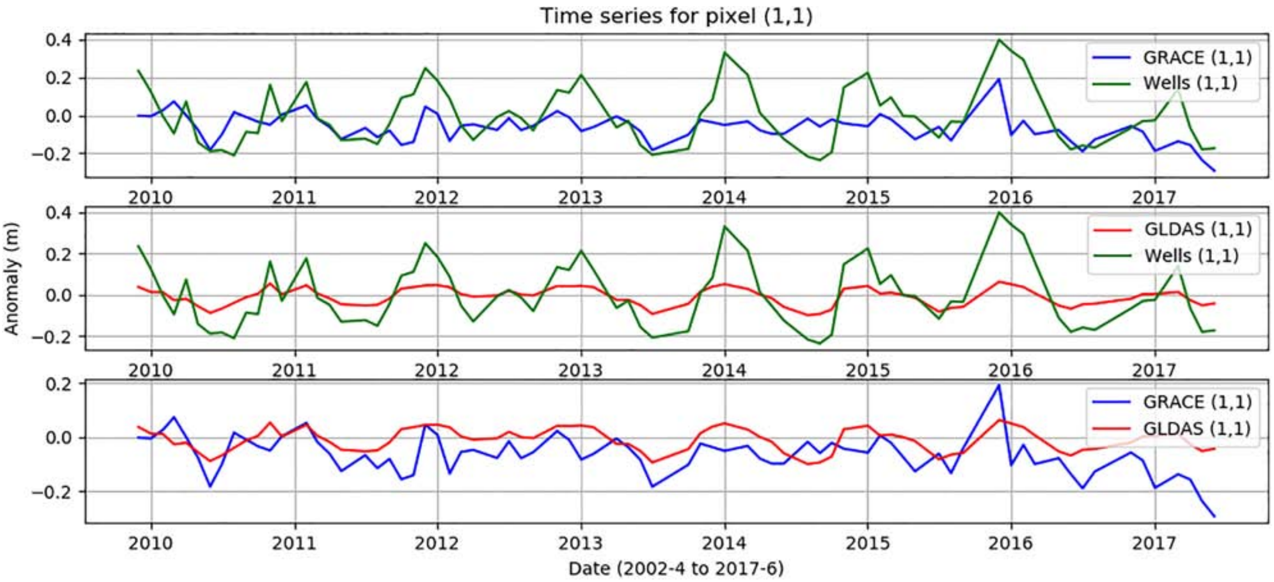

**Figure 3.7. Time series of GRACE, GLDAS and HydroNet well data for pixel (1,1), including Galway, Roscommon and part of Mayo. The well values have been reduced by a factor of 10 to scale the amplitude for plotting purposes.**

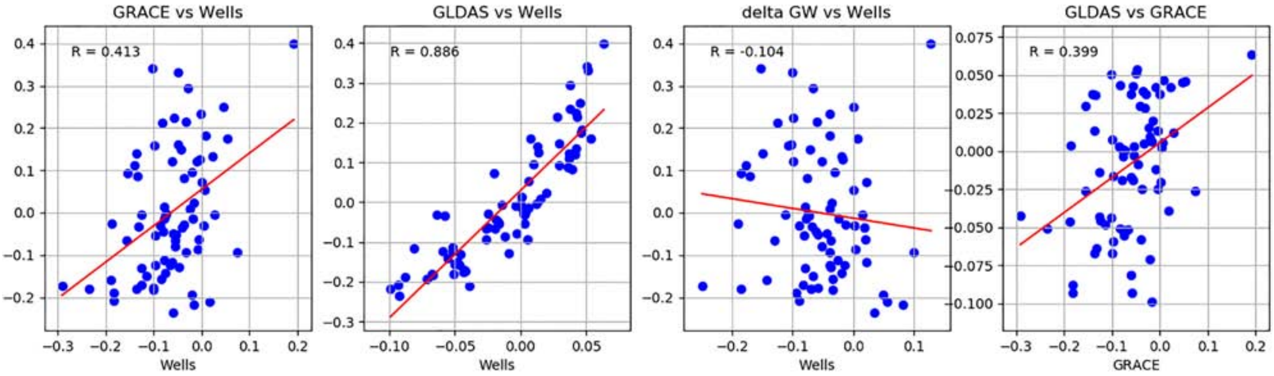

**Figure 3.8. Scatter plots of GRACE, GLDAS, calculated groundwater (delta GW) and HydroNet well data with trend lines fitted using linear regression analysis for pixel (1,1) for the period December 2009 to July 2017.**

into Northern Ireland and has the fewest wells, which were sparsely distributed and almost entirely confined to the edges of the area. The time series in Figure 3.9 show that GRACE and GLDAS data generally track the measured groundwater seasonal pattern, but, with the exception of the GLDAS–GRACE pair, the correlations between the parameters are either very low or non-existent (Figure 3.10). This poor correlation may be partly explained by the apparent offset in the well values in the earlier part of the series up to about mid-way through 2011; values before this date are significantly lower than for the rest of the period. Notwithstanding this, the time series do illustrate a generally good temporal alignment over the whole study period.

The phase shift apparent in some of the time series shown for the four selected pixels may have its origin in the physical dynamics of either aquifer recharge or groundwater movement. Recent work by Rzepecka and Birylo (2020) also found similar lags between the GRACE and groundwater signals. To examine this more closely, time-lagged cross-correlations were calculated, where the Pearson *R* correlation

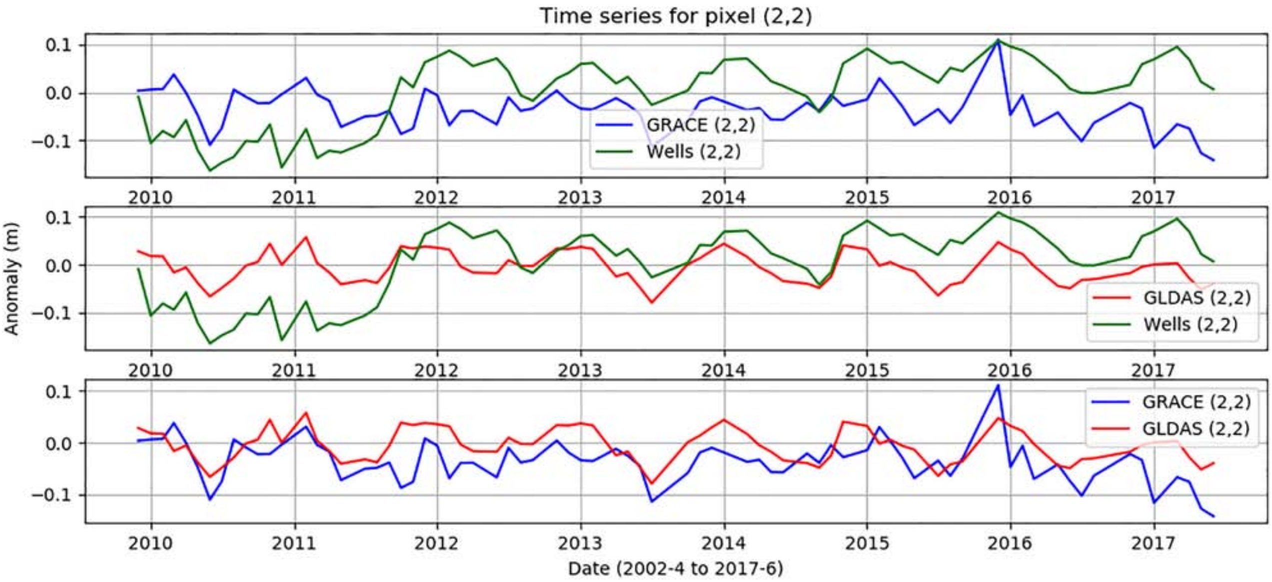

**Figure 3.9. Time series of GRACE, GLDAS and HydroNet well data for pixel (2,2), including parts of Cavan, Monaghan, Leitrim, Donegal, Fermanagh, Tyrone and Derry. The well values have been reduced by a factor of 10 to scale the amplitude for plotting purposes.**

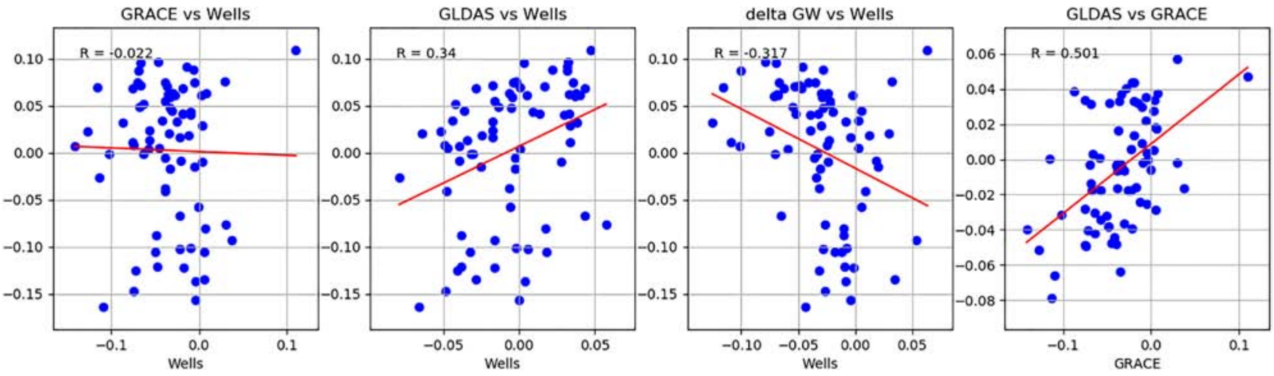

**Figure 3.10. Scatter plots of GRACE, GLDAS, calculated groundwater (delta GW) and HydroNet well data with trend lines fitted using linear regression analysis for pixel (2,2) for the period December 2009 to July 2017.**

coefficient was repeatedly calculated between two series while shifting one of the series by integer time increments to determine the temporal offset at which the maximum correlation occurs. For each pair of time series examined here, one of the series was offset over a range of 4 months in each direction (±4 months offset) and the Pearson *R* calculated at each step. Figure 3.11 shows this analysis for GRACE and wells for all four pixels.

In the case of pixel (1,3), it can be clearly seen that the correlation is maximised, with an *R* value approaching 0.6 when the GRACE signal is shifted to lead the well signal by 1 month. This is also the case for the southern (0,2) pixel, although the effect is less pronounced here, with a smaller increase in *R* value. For the western pixel, the maximum correlation occurs when there is no time shift between the two signals and, because there was essentially no correlation between GRACE and well data for the northern pixel (2,2), the time-lagged analysis produced no meaningful results here.

A similar analysis was carried out with the GLDAS and well data series, and the results for all four pixels are plotted in Figure 3.12. The only pixel that shows a clear increase in correlation here is the eastern (1,3) pixel, where the *R* value increases above 0.6 when

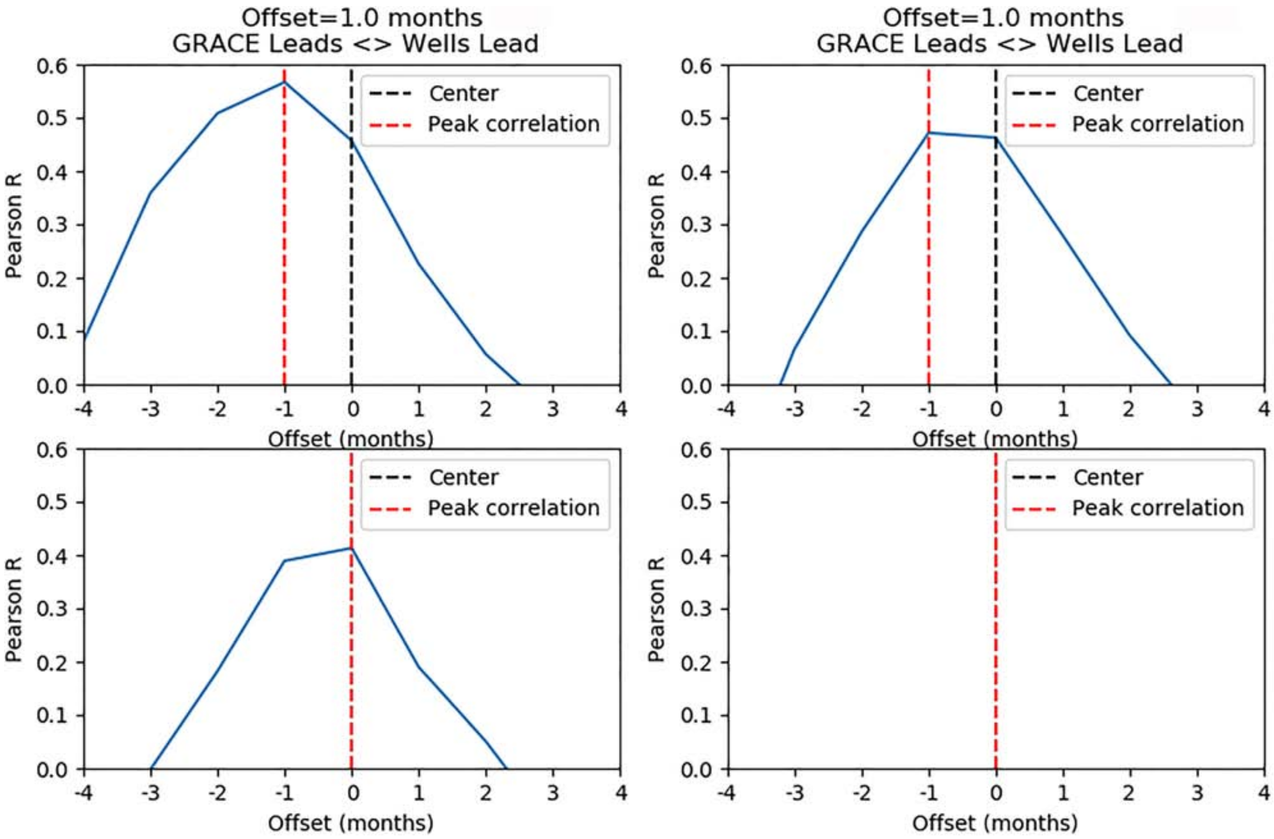

**Figure 3.11. Time-lagged cross-correlations of GRACE and HydroNet well data for all four 1° pixels: (1,3), eastern pixel (top left); (0,2), southern pixel (top right); (1,1), western pixel (bottom left); and (2,2), northern pixel (bottom right).**

the GLDAS signal is shifted to lead the well signal by 1 month. For the other three pixels, the GLDAS and well signals correlated best with no time offset.

The time-lagged cross-correlation analysis between GRACE and GLDAS signals showed that they were best correlated when temporarily aligned with no shift in either direction, as shown in the plots in Figure 3.13.

Finally, the same time-lag analysis was carried out for the calculated groundwater (ΔGWS) and the well data, but, because of the generally very poor correlation between these two parameters, the results, shown in Figure 3.14, are less clear than in the other three cases, and there is no evidence that a time shift produces a better correlation between the two signals in any pixel.

## 3.2 GRACE Mascon Data

As described earlier, GRACE data are also available as mascon data. Although the data are provided on a 0.5° grid, each data point represents a spherical cap 3° mascon and therefore a much larger area than a 0.5° pixel, resulting in considerable leakage between data points plotted at a resolution of 0.5°. It is, however, of interest to also examine this dataset in the Irish context and compare time series of GRACE mascon anomaly values with measured well values. As before, four pixels were selected for closer study and well values representing a 0.5° pixel were calculated by averaging the values of all wells within the pixel. The map in Figure 3.15 shows the locations of the four selected pixels and the number of wells found in each. The two eastern pixels, (1,5) and (2,6), contain 4 and 19 wells, respectively, whereas the two pixels in the western side of the country, (2,2) and (3,1), each contain four wells. A description of the location, underlying aquifer type and the number of wells in each pixel is given in Table 3.2.

The GRACE and well time series are plotted in Figure 3.16 and, in a similar fashion to the time series plots of the 1° pixel data, these time series show that the GRACE mascon signal tracks the groundwater signal as measured by the wells. Correlations between the GRACE and well signals are also roughly similar

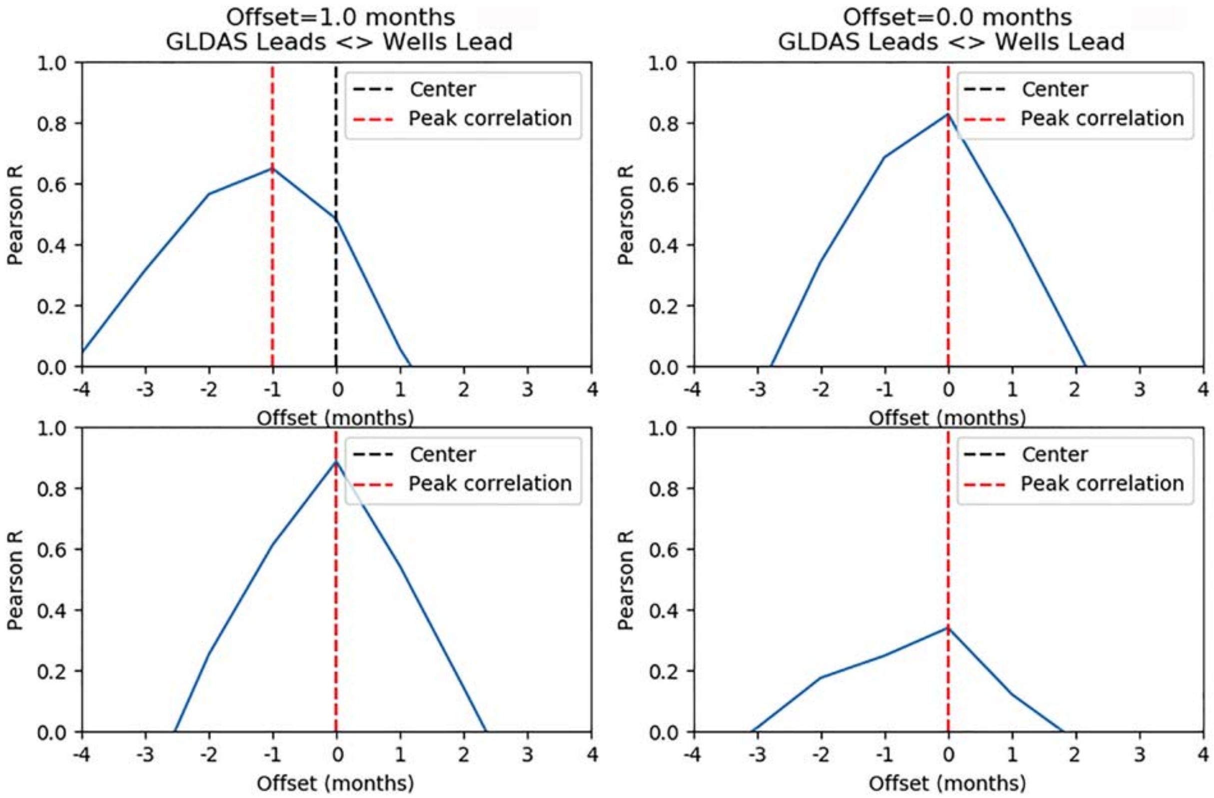

**Figure 3.12. Time-lagged cross-correlations of GLDAS and HydroNet well data for all four 1° pixels: (1,3), eastern pixel (top left); (0,2), southern pixel (top right); (1,1), western pixel (bottom left); and (2,2), northern pixel (bottom right).**

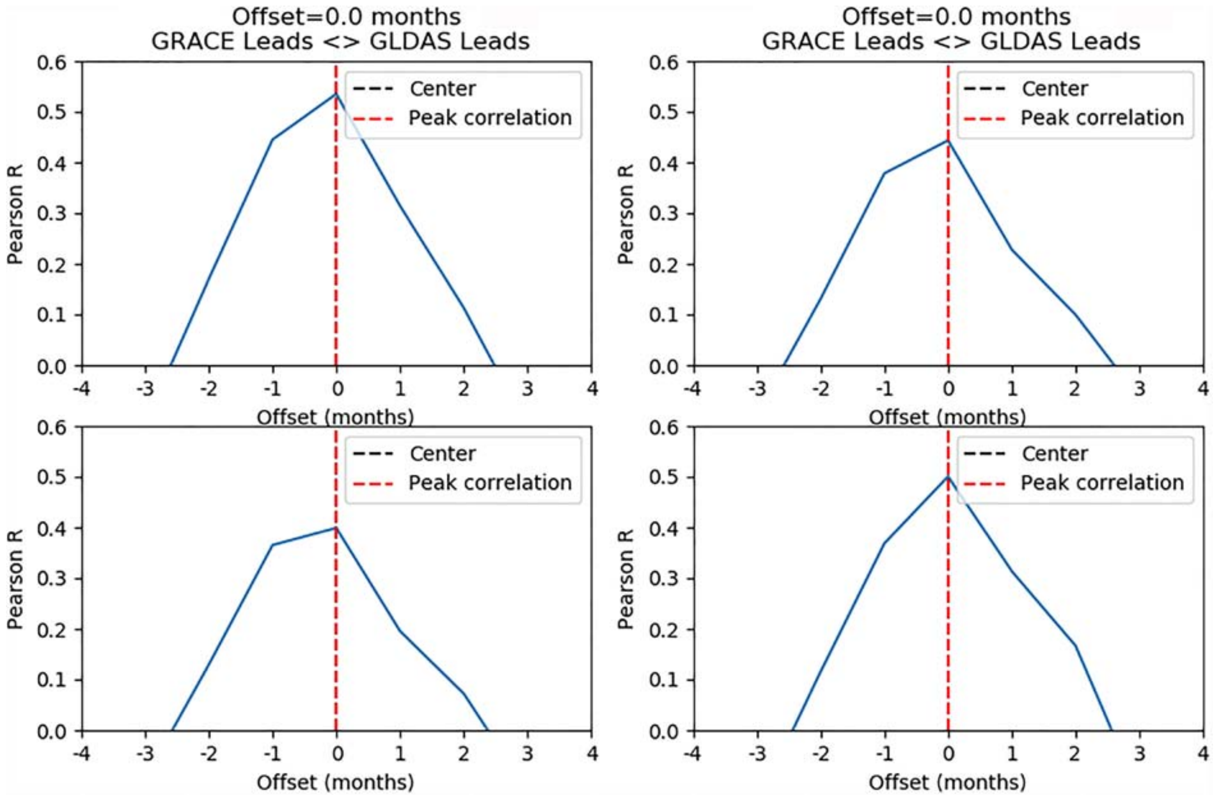

**Figure 3.13. Time-lagged cross-correlations of GRACE and GLDAS data for all four 1° pixels: (1,3), eastern pixel (top left); (0,2), southern pixel (top right); (1,1), western pixel (bottom left); and (2,2), northern pixel (bottom right).**

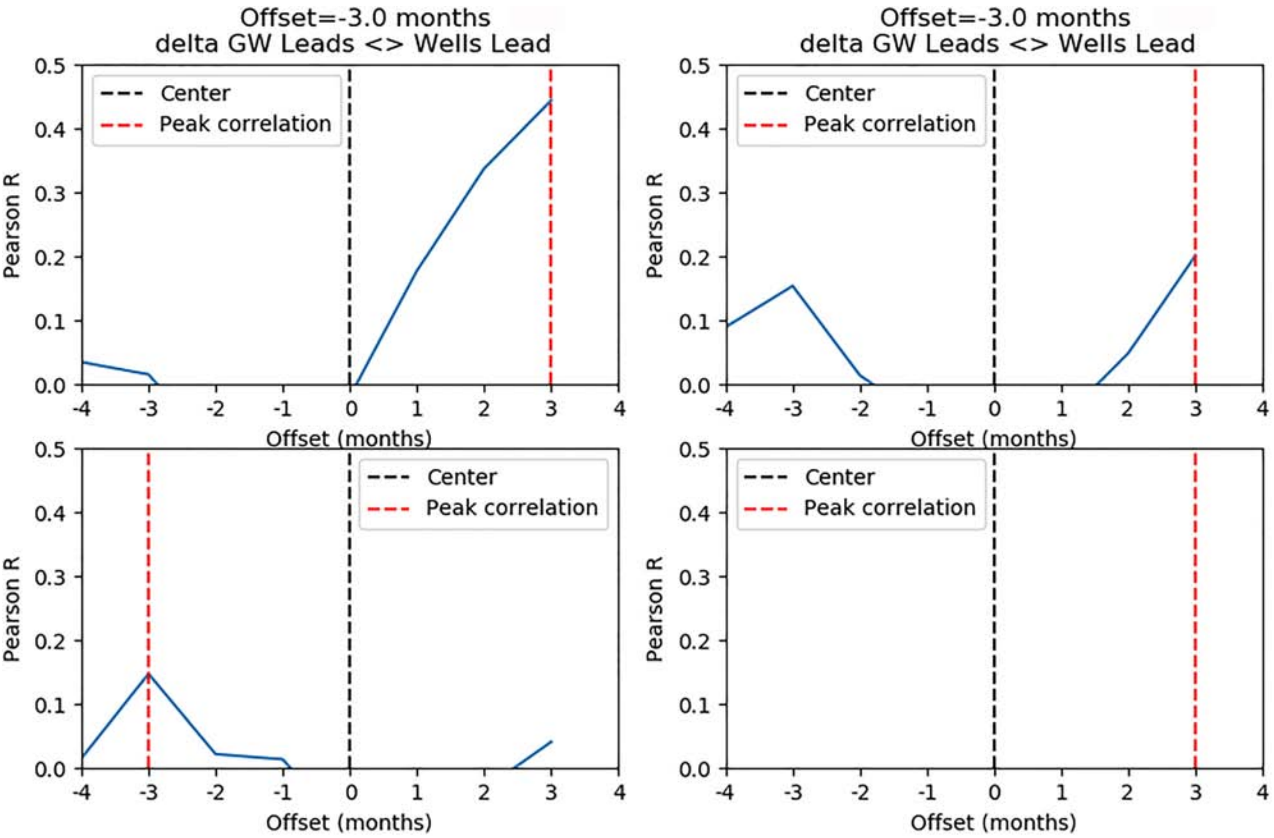

**Figure 3.14. Time-lagged cross-correlations of calculated groundwater and HydroNet well data for all four 1° pixels: (1,3), eastern pixel (top left); (0,2), southern pixel (top right); (1,1), western pixel (bottom left); and (2,2), northern pixel (bottom right).**

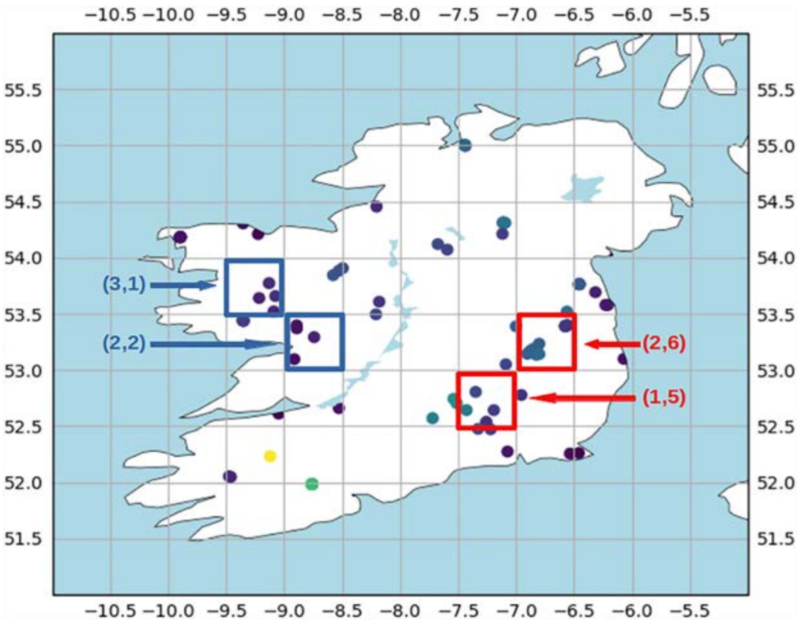

**Figure 3.15. Map of Ireland on 0.5° latitude–longitude grid showing well locations, measured groundwater depth for April 2010 and the pixels selected for case study. The colour of each well point represents the well depth for this particular time snapshot: the lighter the colour, the greater the depth.**

**Table 3.2. Description of the location and underlying aquifer types for the four selected 0.5° pixels, and the number of wells within each pixel**

| Pixel location | | Bedrock aquifer type | Number of wells |
|---|---|---|---|
| (1,5) | Mostly in Kilkenny | Mixture of regionally important karst field (diffuse) and locally important moderately productive bedrock | 4 |
| (2,6) | Includes parts of Kildare and Meath | Mostly locally important, moderately productive bedrock | 19 |
| (2,2) | West Galway | Mostly regionally important karst field (conduit) | 4 |
| (3,1) | West Mayo | Mostly regionally important karst field (conduit) | 4 |

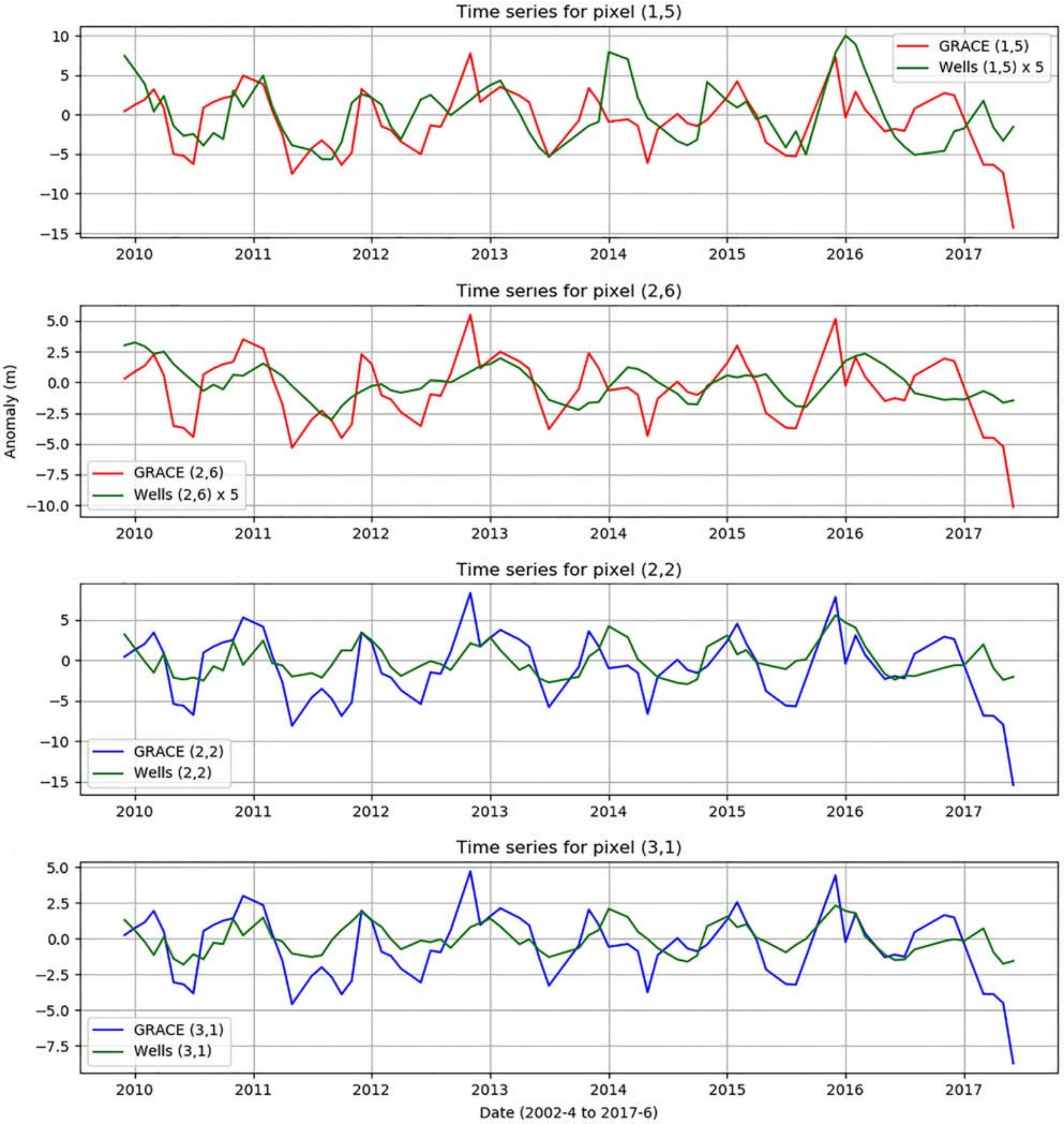

**Figure 3.16. Time series of GRACE mascon data and average of HydroNet well data for four selected pixels: (1,5) and (2,6), the eastern pixels; and (2,2) and (3,1), the western pixels. The well values have been reduced by a factor of 10 to scale the amplitude for plotting purposes.**

to those obtained for the 1° land mass grid (spherical harmonics) GRACE data, with *R* values of about 0.5 for all except one pixel, as shown in the plots in Figure 3.17.

Time-lagged cross-correlations were calculated for the four pixels, and the results are plotted in Figure 3.18. The eastern pixels, (1,5) and (2,6), which both have underlying bedrock aquifers, show the GRACE data leading the wells by about a month, with the effect more pronounced in the (2,6) pixel, which has almost all moderately productive bedrock aquifers, than in the (1,5) pixel, which has a mixture of both moderately productive bedrock and regionally important karst field (diffuse) aquifers. For both western pixels, (2,2) and (3,1), the best correlation between the GRACE and well data is seen where no time is offset between the two time series.

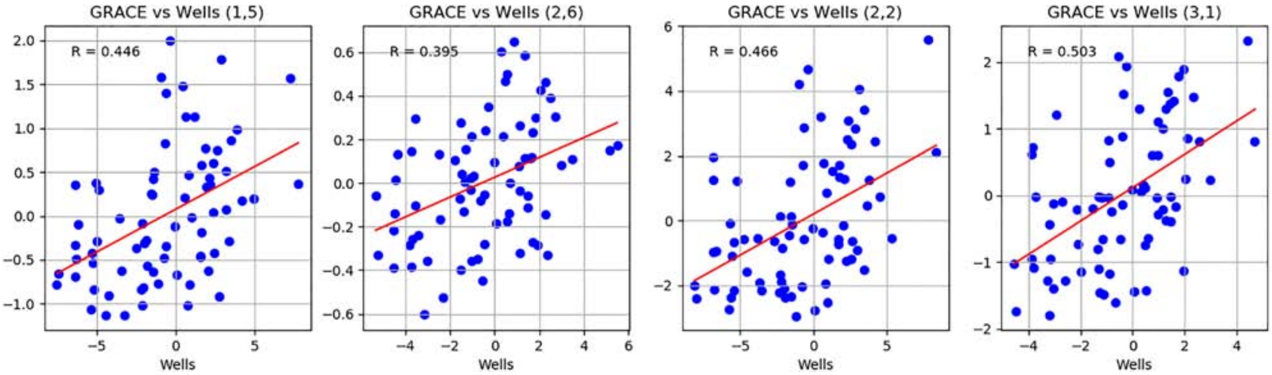

**Figure 3.17. Scatter plots of GRACE mascon and average HydroNet well data with trend lines fitted using linear regression analysis for four selected 0.5° pixels.**

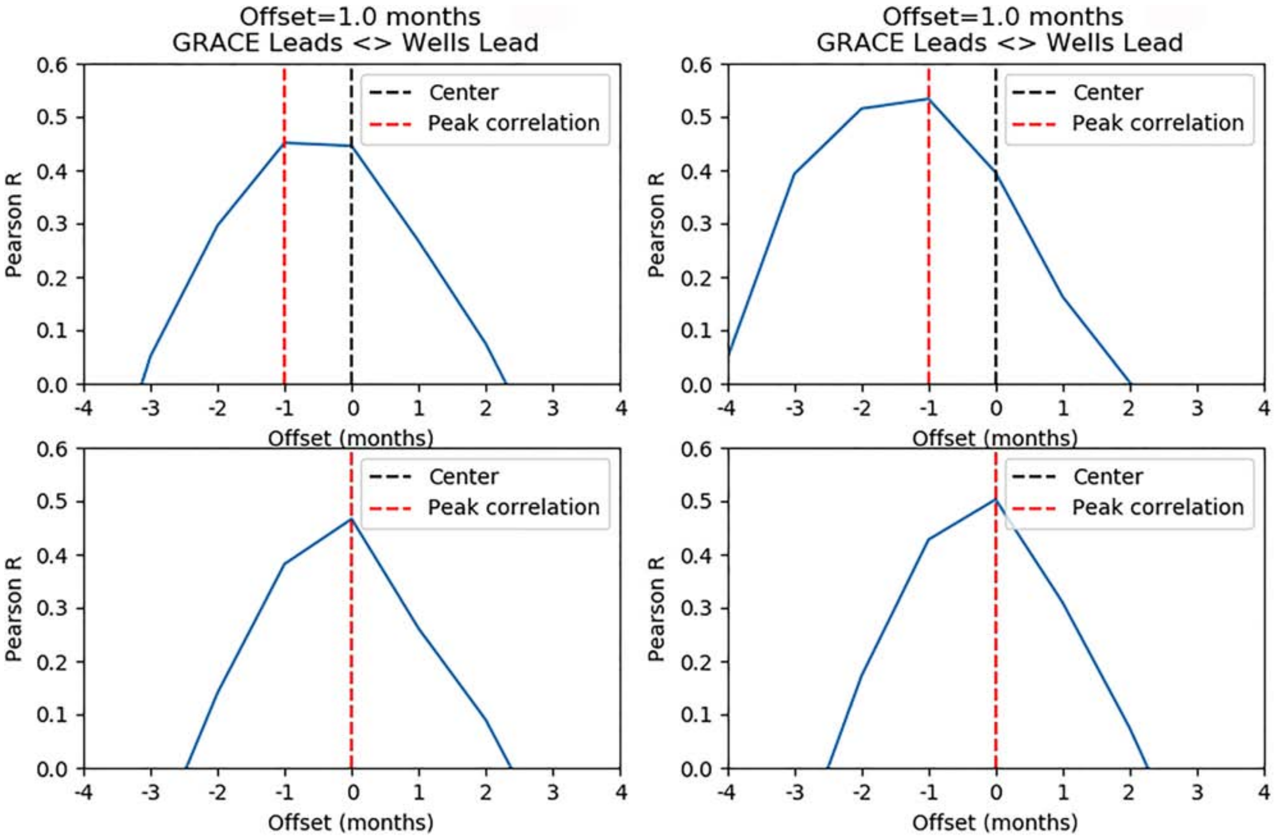

**Figure 3.18. Time-lagged cross-correlation of GRACE mascon and HydroNet well data for the four case study pixels: (1,5), eastern pixel (top left); (2,6), eastern pixel (top right); (2,2), western pixel (bottom left); and (3,1), western pixel (bottom right).**

### 3.3 Kriged Wells

One of the key difficulties in comparing groundwater measurements from orbit with those measured by groundwater monitoring wells lies in the colocation of both parameters at the same point on the surface. GRACE land mass grid satellite measurements have a resolution of 1°, meaning that each value of LWE thickness in the GRACE dataset is ascribed the latitude–longitude coordinates of the centroid of the pixel that it is considered to represent. To compare this value with the well measurements within that same pixel requires some method of amalgamating the contributions from all such wells into a single value, which can then be considered to represent the groundwater level as measured by the wells in that pixel. In the previous analysis described here, both at 1° and 0.5° resolutions, a simple arithmetic average of the wells within a pixel located at the centroid of the pixel was calculated. Another method commonly used in this kind of analysis to obtain a single representative value is to krige all of the well point measurements to points on a regular grid located at the centroids of the grid cells.

Kriging is an interpolation technique, with its origins in geostatistics, originally developed by Danie G. Krige (1951) in an attempt to estimate the most likely distribution of gold from a sparse network of boreholes for mining purposes. When applied to the movement or location of groundwater, which is heavily dependent on the nature and geometry of the containing aquifer, there is likely to be greater uncertainty in the degree to which calculated kriged values accurately represent underlying groundwater volume and distribution. The effect of this potential uncertainty is likely to be greater where the kriged values are calculated over grid cells that include diverse and inhomogeneous underlying aquifer types or where the distribution and average depth of the wells within a pixel are highly variable. Both of these apply in the Irish context over most of the country and the network of monitoring wells, which leads to the potential for considerable uncertainty in the degree to which kriged values of well depths accurately represent real groundwater dynamics. However, it is still of interest to compare a regular kriged well grid with a co-located GRACE grid, particularly in view of the fact that any attempt to successfully downscale GRACE measurements will rely on a good kriging scheme to develop a grid of well measurements, which will, as accurately as possible, represent the real measured groundwater levels at the required higher resolution. The analysis presented here is a first step in this pursuit.

The kriging scheme adopted here was ordinary two-dimensional kriging using a spherical variogram

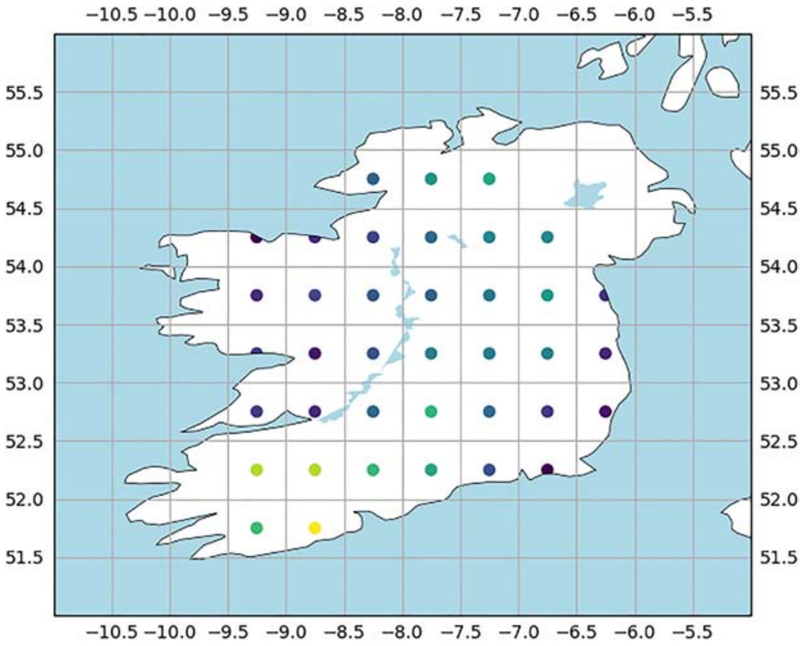

**Figure 3.19. Kriged well measurements at 0.5° resolution; example from April 2010. The colours of the well points represent the well depth for this particular time snapshot: the lighter the colour, the greater the depth.**

model, where the model parameters, nugget, sill and range, were automatically calculated by fitting the variogram model to the binned experimental semivariogram. The entire network of 110 active wells used in this study was kriged to the centroids of 0.5° pixels for each of the 74 1-monthly time steps; an example of one such month (April 2010) is shown in Figure 3.19, which shows the kriged well values plotted on a 0.5° latitude–longitude grid, with the colours of the points representing well depth (lighter colours represent greater well depth). Variances from the long-term means were calculated as previously, and these values were compared with the GRACE mascon anomalies.

Time series of GRACE mascon anomalies were plotted together with time series of kriged wells for the same four selected pixels as in section 3.2, shown in Figure 3.20. In general, the GRACE signal again appears to track the kriged well signal in most cases. The spikes in the kriged well series evident in pixels (1,5) and (3,1) may be due to the high variations in the well values at that point in time. Correlations for each pixel were calculated as before, and these results are

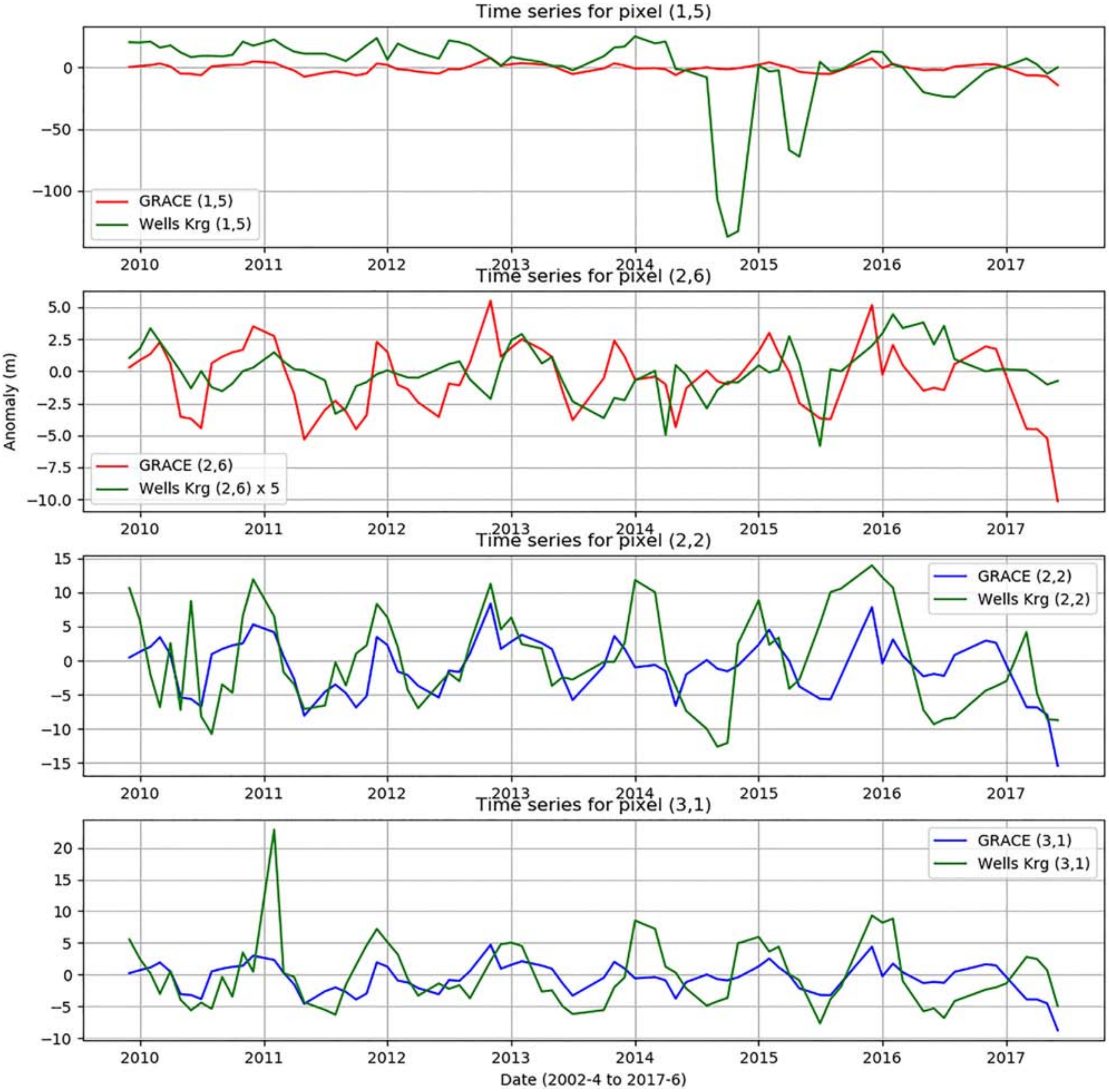

**Figure 3.20. Time series of kriged well data and GRACE mascon data for all four selected 0.5° pixels. The well values have been reduced by a factor of 10 to scale the amplitude for plotting purposes.**

shown in Figure 3.21. The correlation is very poor for the two eastern pixels, (1,5) and (2,6), with *R* values of 0.3 or less, but slightly better for the two western pixels, with both *R* values being just over 0.4. In general, however, these correlation values are lower than those obtained by comparing the GRACE mascon values with averages of the well measurements within each pixel.

Time-lagged cross-correlation analysis reveals that the GRACE mascon signal may be leading the kriged well groundwater measurements by about 2 months in the (2,6) eastern pixel, as shown in the plots in Figure 3.22. No time offset is observed in the other three pixels.

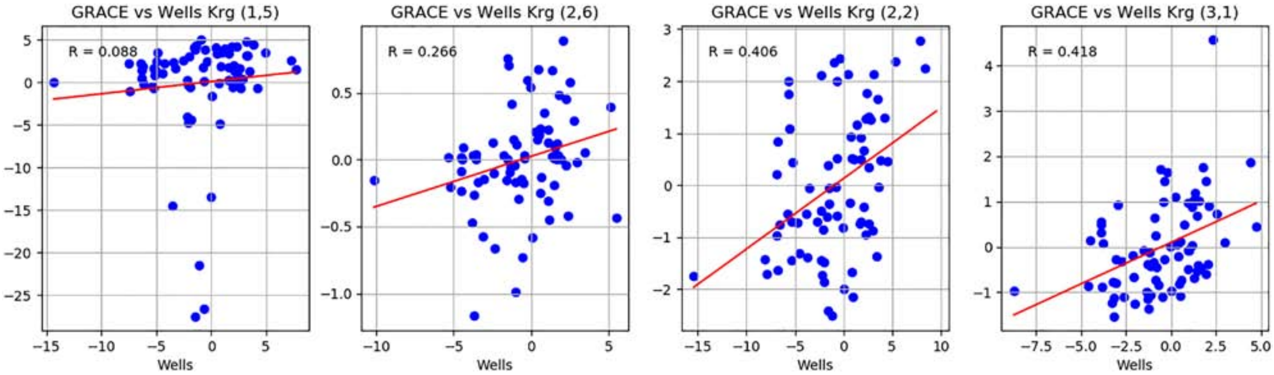

**Figure 3.21. Scatter plots of GRACE mascon and kriged well data with trend lines fitted using linear regression analysis for four selected 0.5° pixels.**

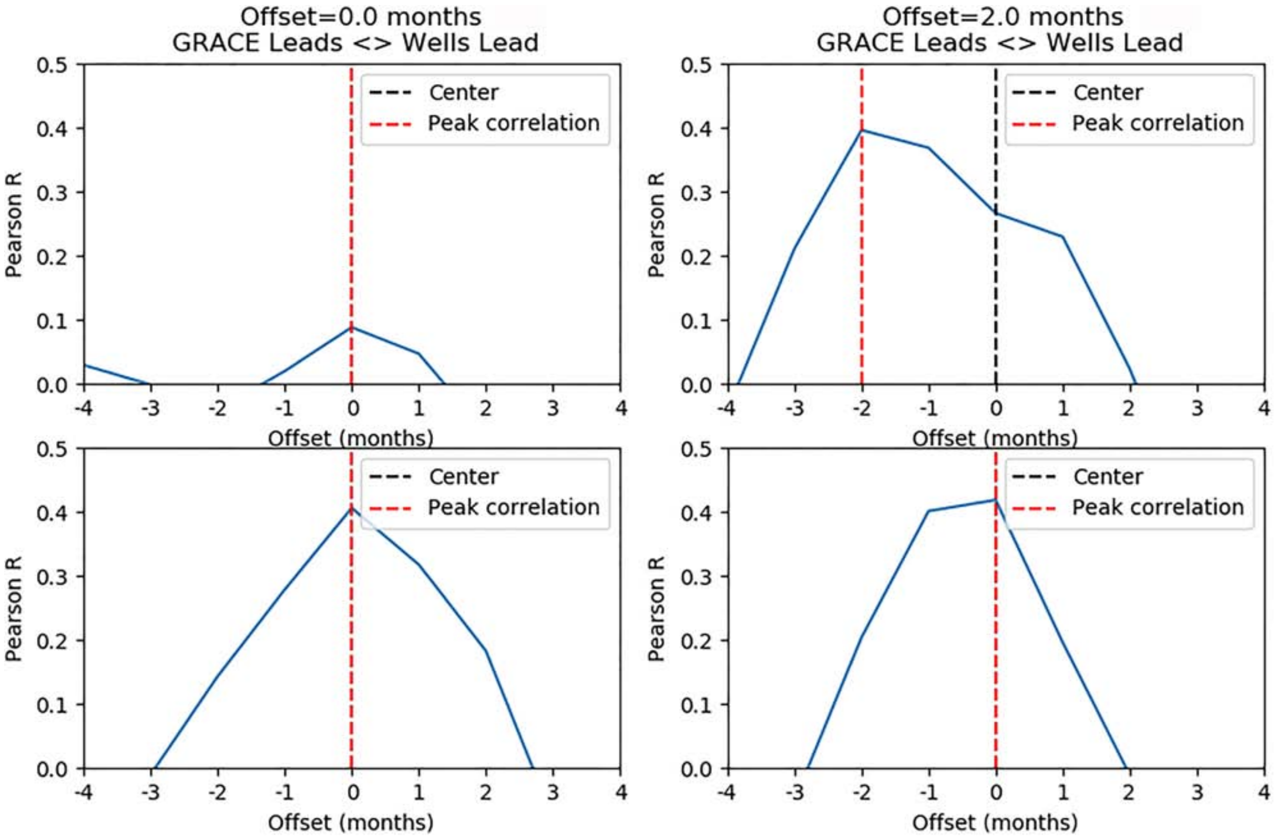

**Figure 3.22. Time-lagged cross-correlations of GRACE mascon and kriged well data for the four case study pixels: (1,5), eastern pixel (top left); (2,6), eastern pixel (top right); (2,2), western pixel (bottom left); and (3,1), western pixel (bottom right).**

This analysis of the correlation between the GRACE mascon and kriged well data is generally consistent with the previous analysis of the 1° land mass grid GRACE data, although the correlation coefficients are slightly lower, which may be due to the parameters of the semivariogram used in the kriging calculations, but may also be due to the degree to which the kriged well values accurately represent the real groundwater values at the coordinates on the kriged grid. This is by itself an area of considerable complexity that warrants further study to optimise the kriging scheme to the particular characteristics of the region in question. Machine learning-based kriging models have been implemented in the PyKrige Python library to address these kinds of problems and should be incorporated into future efforts to derive the most accurately representative kriged well grids for comparison with GRACE measurements.

# 4 Discussion

From its inception and the first general availability of data in 2002, the GRACE mission offered great potential for application to diverse areas of research within the geosciences. Although the mission was very quickly successful in mapping the gravitational potential field of Earth, the extension to hydrological applications took a little longer to develop and gain general acceptance. As outlined in Chapter 1, early successful studies over the Amazon basin, Indian subcontinent and even the Sahara desert established its credentials in the field of hydrology. Through the continued refinement of the measurements themselves, and active innovation in data reduction and increasingly complex and sophisticated analysis techniques by researchers all over the world, the development of GRACE as a tool in the operational detection, monitoring and management of groundwater resources is now a rapidly advancing field. In this context, the current study is another small step towards placing GRACE more centrally in the toolkit at the disposal of scientists, policymakers and managers in the development of reliable long-term operational systems to optimally exploit groundwater resources, which are increasingly under pressure.

The state of the art typically involves the use of many additional datasets in combination with GRACE measurements to refine the accuracy of tracking groundwater variation over time. Starting from baseline estimates of surface water from land surface models such as GLDAS and direct groundwater measurements from wells – such as those used for this study – more sophisticated modelling involves data including meteorological parameters, surface elevation, soil type and temperature data, vegetation indices, and measured surface water and lake stage data. The use of these types of datasets in combination with suitable machine learning schemes has been successful in downscaling GRACE measurements to a scale much smaller than the original 1° resolution of the GRACE land mass grids or the 3° resolution of the GRACE mascon data, particularly over relatively large and geologically homogeneous areas, and especially where the underlying aquifers are relatively uniform over the area. This has been shown to be the case for example in studies over the California Central Valley (Miro and Famiglietti, 2018) and large areas in Michigan, USA (Sahour *et al*., 2020). A prerequisite to any such efforts, however, is that the GRACE measurements must at least consistently track the groundwater measurements and follow similar patterns of seasonal changes. Time offsets in these time series may reflect the characteristics of the different surface strata and the aquifers, such as porosity and aquifer type (bedrock, karst field and so on).

Recent studies elsewhere have reported strong correlations between GRACE mascon data and groundwater well measurements without downscaling, particularly over regions with relatively homogeneous underlying geomorphology and aquifer types and at large river-basin scale spatial resolutions. Katpatal *et al*. (2018) studied an area of central India covered by about four 1° GRACE pixels composed of a simple aquifer system in the western region and a complex aquifer in the eastern region, which enabled them to compare the sensitivity of GRACE for analysing groundwater storage in both types of aquifer. Their results demonstrate the ability of GRACE to detect GWS anomalies in both types of aquifers, with greater correlation and therefore accuracy in the simple aquifer region. The values of Pearson *R* correlation coefficient of about 0.5 to 0.6 that they obtained for the complex aquifer region closely match the values obtained in our study. The concordance of the results of this work with those of Katpatal *et al*. (2018) and other recent studies is not simply reassuring, it also critically adds to the growing evidence for the applicability of GRACE groundwater measurements, not just to large-scale hydrogeologically homogeneous regions with relatively uniform aquifer types, but also to areas that encompass many different types of underlying aquifer over a small area, such as Ireland. Combined with the well-constructed complex and powerful machine learning models reported in other studies, also over complex aquifer regions, the current results suggest that a similarly effective system could in principle be developed for the Irish context.

# 5 Conclusions

In this study, we have examined the relationships between GRACE measurements and groundwater well measurements over the Irish land mass to ascertain if it is possible to determine groundwater variations from GRACE data that correlate with data from the existing groundwater well network. The time series and correlation analysis show that these two sets of measurements are indeed reasonably well correlated, given the range of uncertainty in both datasets, and that this is the case for GRACE 1° land mass grid data and also for GRACE mascon data. Groundwater well data have been compared with GRACE data, both by averaging the wells within a particular pixel and also by kriging the wells to the centroids of the 0.5° pixels in the case of the GRACE mascon data. The same correlation patterns were seen in both cases. These results suggest that the GRACE measurements track groundwater variations as measured by the well network over Ireland at the spatial resolution of the GRACE datasets.

The time lags seen between the GRACE and well signals most likely reflect physical processes in some of the pixels studied. In particular, the GRACE signal leads the well groundwater measurements by about 1 month for pixels located in the eastern side of the country for both the GRACE land mass grids and the GRACE mascon data; in contrast, no such time lag is apparent in the west. These eastern pixels are located in areas where the underlying aquifers are classified as moderately productive bedrock; the time offset between the water being detected by GRACE and it being measured by the wells suggests that the delay between water being delivered to the surface, whether by precipitation or run-off or other means, and it recharging the aquifer beneath is about 1 month. This may be attributable to the porosity of the upper soil strata and the nature of the aquifer itself. It should be noted, however, that a time lag of 1 month may not be accurately representative of the actual aquifer recharge time; the lag time estimate is limited by the 1-month temporal resolution of the data and is likely to be less than 1 month in most cases. No time offset is seen in pixels overlying karst field aquifers in the western half of the country, which seems to indicate there is only a very thin and highly porous soil layer or no soil layer or that the underlying aquifers are recharged almost immediately through fissured porous substrata.

The GRACE signal represents all gravitational anomalies detected in the satellites' flight path; although most of these variations can be attributed to changes in groundwater volume and location, changes in water stored in all of the higher surface layers, including soil, snow and vegetation, also contribute to the GRACE anomalies detected. To isolate the groundwater signal, these contributions from the non-groundwater strata must be calculated or estimated and subtracted. The most common current method of doing this is to subtract the estimates of SM, SWE and CA provided by the GLDAS land model from the total GRACE terrestrial water measurement value. In this study, we have calculated the GLDAS components of surface water over Ireland corresponding to the GRACE time series and subtracted these to obtain the derived groundwater signal. In contrast to the original GRACE data, the groundwater time series calculated using this method do not exhibit the same strong seasonal variations and do not correlate well with the groundwater time series measured by the wells. This could be a consequence of the more homogeneous representation of SM globally by the GLDAS model, in contrast to the highly heterogeneous situation in Ireland, particularly given the prevalence of small surface water bodies and bogs. Previous work has demonstrated the deficiencies of accurately quantifying SM in boreal and sub-Arctic regions, which are dominated by such surface features, using standard land surface models such as the GLDAS framework (Naz *et al.*, 2020). The use of more sophisticated and locally applicable land surface models would be likely to yield non-groundwater time series of greater fidelity and so provide a more accurate derived groundwater signal from the GRACE data.

As already highlighted, the key limitation when attempting to detect groundwater from orbit using data from the GRACE satellites is spatial resolution. The GRACE land mass grids (spherical harmonics-derived data) have a resolution of 1° latitude–longitude and the mascon data, although provided on a 0.5° grid, represent 3° spherical cap mascon data. To resolve details on a smaller scale requires downsampling of the GRACE datasets to higher spatial resolutions. Techniques involving a number of different machine learning schemes and algorithms and additional datasets have been described in the literature, and considerable success has been reported, particularly in areas where the underlying aquifer types are relatively uniform over the studied area and where enough additional relevant datasets are available at suitable resolution to conduct these kinds of analyses. Notable examples of such studies include Miro and Famiglietti (2018) in the California Central Valley, Seyoum *et al*. (2019) in Illinois and Sahour *et al*. (2020) in Michigan, all of which employed sophisticated downscaling machine learning-based models involving a number of additional datasets that were carefully prepared, stratified, classified and clustered to most accurately represent the measured quantities. These studies have all highlighted the fact that the construction of a suitable machine learning-based model is not a trivial exercise, but requires the careful selection and a great deal of preparation of many input datasets informed by geological and hydrological expertise, to enable the selection of the best kinds of data, that is, the data most relevant for analysing effects on groundwater levels for a particular region. This is particularly true where the region in question has a highly heterogeneous underlying geomorphology and aquifer system, as is the case over almost all of the Irish land mass. Although modelling of this kind was beyond the scope of this study, the current work has established the essential first step of characterising the GRACE land mass grid and GRACE mascon measurements over Ireland, and determining the extent to which these are correlated with the real groundwater well measurements.

In general, however, the GLDAS model data series correlates very well with the groundwater well measurements, with particularly high correlations for some pixels, the highest correlations occurring in pixels with mostly or some karst field aquifers. This appears to indicate a very short aquifer recharge time for these aquifer types. Furthermore, although using a combination of GLDAS and GRACE data to produce estimates of groundwater as seen from orbit over Ireland does not produce inferred groundwater results that correlate well with the actual groundwater levels measured by the wells, the strong correlation between the GLDAS-modelled values and values measured by the wells suggests that the GLDAS model captures the variability of the measured groundwater with a high degree of accuracy. This does suggest that, generally, the dominant variable groundwater signal across Ireland can be accurately modelled to be within 2 m of the surface, as is the case for the GLDAS land surface model.

# 6 Recommendations

The work conducted in the course of this project has, above all, revealed that this is a very dynamic area of research and, in particular, that efforts to downscale GRACE measurements, especially over complex aquifer terrain, are very much a work in progress. Significant successes have been reported in recent publications, however. Although the geomorphology and aquifer systems in Ireland present their own unique challenges, studies in other parts of the world with similarly complex features have had notable success in developing sophisticated machine learning-based models to achieve useful downscaled resolution, suggesting that a similar model could be developed for Ireland. This study has also revealed that the construction of such a model is a considerably greater task than perhaps originally anticipated, requiring many additional datasets and considerable work in the preparation and integration of these datasets into the model. However, the fact that the GLDAS model captured the variability of the directly measured groundwater with a high degree of accuracy, and in a way that was almost entirely concordant with the total water anomaly as measured by GRACE, does make a very strong case for investing in the development of an Ireland-specific land surface model of groundwater variation.

With this in mind, a number of recommendations to progress this endeavour have arisen from the work to date presented here.

1. Consideration should be given to the development of an Ireland-specific land surface model to better capture soil moisture variations to a depth of 2 m, a depth that would appear to be sufficient to capture the dominant groundwater contribution as determined by GRACE. Such an initiative would involve the relevant national stakeholders, including the EPA, GSI and Teagasc.
2. Further work, following on from the initial results presented here, would be required to further develop a prototype machine learning-based model of groundwater detection by GRACE satellite measurements, incorporating many relevant datasets to address the particular complexities of the Irish aquifer profile that may be applicable in specific locations/regions in Ireland.
3. The integration of multiple datasets into either model will require the development of software interfaces and APIs to facilitate the reliable operational use of these datasets.
4. Regular communication among, and review by, relevant stakeholders regarding which datasets might be considered relevant for inclusion into either of these models is also important.
5. The development of a representational state transfer (RESTful) API is required to facilitate computational access to the database hosting measurements from the EPA's HydroNet network, and a similar approach would need to be adopted by GSI for its groundwater well network.
6. Additional monitoring wells located in areas that are currently sparsely monitored are required to provide fully representative groundwater monitoring.
7. A web-based interface should be developed to provide access to model estimates, measurements and predictions in real time.

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# Abbreviations

| | |
|---|---|
| **API** | Application programming interface |
| **ASCII** | American Standard Code for Information Interchange |
| **CA** | Canopy water |
| **CSR** | Center for Space Research |
| **CSV** | Comma-separated value |
| **DLR** | German Aerospace Centre |
| **EPA** | Environmental Protection Agency |
| **GLDAS** | Global Land Data Assimilation System |
| **GRACE** | Gravity Recovery and Climate Experiment |
| **GRACE-FO** | Gravity Recovery and Climate Experiment Follow-on |
| **GSFC** | Goddard Space Flight Center |
| **GSI** | Geological Survey Ireland |
| **GWS** | Groundwater storage |
| **JPL** | Jet Propulsion Laboratory |
| **L1** | Level 1 |
| **L2** | Level 2 |
| **L3** | Level 3 |
| **LWE** | Liquid water equivalent |
| **Mascon** | Mass concentration |
| **NASA** | National Aeronautics and Space Administration |
| **netCDF** | Network common data form |
| **SM** | Soil moisture |
| **SWE** | Snow water equivalent |
| **TWS** | Terrestrial water storage |

**AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL**
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

## Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

**Rialú:** *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

**Eolas:** *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

**Tacaíocht:** *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

## Ár bhFreagrachtaí

### Ceadúnú

Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:

- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

### Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

### Bainistíocht Uisce

- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

### Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol

- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

### Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn

- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

### Taighde agus Forbairt Comhshaoil

- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

### Measúnacht Straitéiseach Timpeallachta

- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

### Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

### Treoir, Faisnéis Inrochtana agus Oideachas

- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

### Múscailt Feasachta agus Athrú Iompraíochta

- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

### Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:

- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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# GRACE Monitoring of Groundwater Over Ireland – A Feasibility Study

Authors: Michael Geever, Eve Daly and Aaron Golden

## Identifying Pressures

Changing population trends, growing urbanisation and associated economic development increase pressure on our water resources. In the context of national and EU legislation, attention must now focus on the availability and long-term sustainability of water resources given changing precipitation patterns associated with climate change. This project attempts to assess the value of using space-based observations of gravitational anomalies, obtained by NASA's Gravity Recovery and Climate Experiment (GRACE), to assess groundwater variations at a regional level across the island of Ireland. The most widely used land surface model of surface moisture was used along with data from the EPA's HydroNet groundwater well network. This report highlights the correlation between GRACE estimates of groundwater variations and in situ observations over an 18-year period. The long-term trend suggests consistent and sustained recharging of local groundwater resources across the island with no evidence of abstraction stress on groundwater supplies at a regional level or on abstraction rates. Further work to determine the resilience of local supplies in the event of significant increases in demand due to future industrial development and/or population growth is warranted. The report also identifies an opportunity for the development of a national land surface model, to more accurately capture the island's complex hydrogeological environment and provide a baseline for policy implementation and planning.

## Informing Policy

Given current and projected demands based on Ireland's projected population growth, ongoing economic development and changing agricultural practices, a comprehensive means of monitoring total groundwater storage will be invaluable for policymakers and legislators, to enable Ireland to meet its obligations under national legislation [European Communities (Water Policy) Regulations, 2003 (S.I. No. 722 of 2003); European Union (Drinking Water) Regulations 2014 (S.I. 122 of 2014); European Communities Environmental Objectives (Surface Waters) Regulations, 2009 (S.I. No. 272 of 2009); European Communities Environmental Objectives (Groundwater) Regulations, 2010 (S.I. No. 9 of 2010); European Communities (Good Agricultural Practice for Protection of Waters) Regulations, 2010 (S.I. No. 610 of 2010); European Communities (Technical Specifications for the Chemical Analysis and Monitoring of Water Status) Regulations, 2011 (S.I. No. 489 of 2011)] and EU directives [Water Framework Directive (2000/60/EC), Groundwater Directive (2006/118/EC) and Marine Strategy Framework Directive (2008/56/EC)].

## Developing Solutions

This report fully documents ways of accessing, processing and visualising GRACE gravitational anomaly data, and outlines a means to integrate data from NASA's land surface model with data from the EPA's HydroNet groundwater well network. The GRACE mission team provides two types of gravitational anomaly data, and methods for using both types are presented in the report. The report also described how EPA HydroNet data can be utilised and compared with NASA's GRACE and land surface model data. Given the limited resolution of the GRACE data (~110 × 70 km), solutions are presented for four pixels that capture distinct hydrogeological contexts at cardinal points in Ireland, with the resulting time series data from each resource (GRACE, NASA's land surface model and HydroNet) available for analysis. All analysis methods were developed within the Python programming ecosystem, ensuring portability and ease of use for interested third parties.

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