



Deliverable 4.2

PILOT DESCRIPTION AND ASSESSMENT

South East Midlands aquifers (Ireland)

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This report is part of a project that has received funding by the European Union's Horizon 2020 research and innovation programme under grant agreement number 731166.



Deliverable Data	
Deliverable number	D4.2
Dissemination level	Public
Deliverable name	Pilots description and assessment report for recharge and groundwater vulnerability
Work package	WP4
Lead WP	BRGM, BGS (NERC)
Deliverable status	
Version	Version 2
Date	28/04/2021

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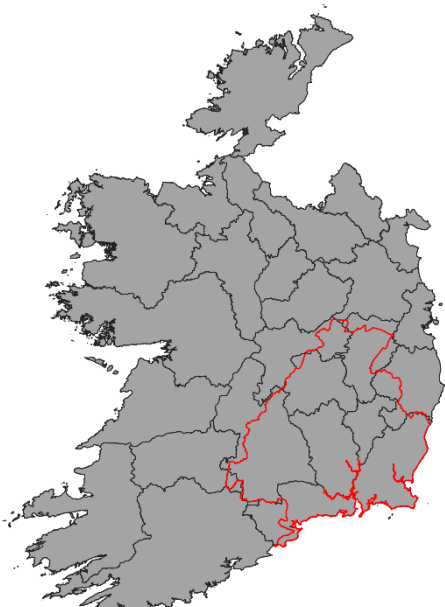
LIST OF ABBREVIATIONS & ACRONYMS

AE or ET_a	Actual Evapotranspiration
DECC	Department of Environment, Climate and Communications
ECMWF	European Centre for Medium-Range Weather Forecast
EPA	Environment Protection Agency
ER	Effective Rainfall
E	evaporation
ET_0 or PE	Reference Evapotranspiration/ Potential Evapotranspiration
f	evaporation factor (for Metran models)
FAO	Food and Agriculture Organisation of the United Nations
GSI	Geological Survey Ireland
ICHEC	Irish Centre for High End Computing
INRM	Irish National Recharge Model
m aOD	meters above Ordnance Datum
m bgl	metres below ground level
MÉRA	Met Éireann ReAnalysis
NWP	Numerical weather prediction
P	precipitation (for Metran models)
R	Rainfall
R	Recharge (for Metran models)
SMD	Soil Moisture Deficit

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1 EXECUTIVE SUMMARY

Pilot name	SE Midlands aquifer	
Country	Ireland	
EU-region	North-western Europe	
Area (km ²)	13,188	
Aquifer geology and type classification	The principal aquifers of interest are (i) pure, bedded limestones: secondary porosity diffusely karstified bedrock aquifers. Groundwater flows within a network of solutionally enlarged fractures and occasional conduits. Some areas are dolomitised giving secondary intergranular porosity. Yields are typically of the order of 5-20 l/sec. (ii) sand/gravel aquifers, where flow and storage is primary intergranular. Yields range from 2.5-15 l/sec. For context: other regionally important aquifers are fissured volcanic rocks with secondary permeability only, and sand/gravel aquifers, where flow and storage is primary intergranular. Minor aquifers are all secondary porosity/permeability fissured bedrock. Over much of the karst limestone, subsoil cover is medium permeability. In parts of the SE of the study area, subsoils are thick and low permeability.	
Primary water usage	Drinking water / Agri-Industry.	
Main climate change issues	Increase in water abstraction over time – irrigation, livestock. Risk of drought. Other issues = water table rebound after mines closures.	
Models and methods used	Conceptual model, Time series analysis (local), satellite (exploratory)	
Key stakeholders	Government. Water companies. Research institutes. Industry. Farming.	
Contact person	Geological Survey Ireland. Taly Hunter Williams .	

This report describes the work undertaken by Geological Survey Ireland (GSI) as a part of TACTIC WP4 to calculate historical and future groundwater recharge in the catchment to selected observation boreholes in the south-east of Ireland. Multiple tools, selected from the TACTIC toolbox that is developed under WP2 of the TACTIC project, have been used for this purpose.

The south-east region encompasses four Regionally-important aquifer types, two of which are assessed in this study, as well as minor aquifers:

(1) karst aquifers are significant in south-east Ireland. These aquifers comprise pure, bedded limestones with zero primary porosity and permeability, but with well-developed and interconnected fracture networks and solution enhancement fractures. In some areas, these aquifers are bedded and massive limestones that have been dolomitised, resulting in patchy secondary intergranular porosity development. The karstified limestones occupy low-lying areas between non-karst hills, and are characterised by an extensive, well-drained rolling landscape. In parts of the area, depending on the orientation of the 'grain' and the river network, karst limestones can occur in relatively narrow river valleys. Much of the aquifer is overlain by glacial deposits of the late Quaternary. These are typically well-drained, and groundwater within the aquifer is mostly unconfined or part-confined. Some areas are overlain by thick low permeability tills (diamicts) or post-glacial peats, and are confined.

(2) large glacio-fluvial sands and gravels form significant groundwater resources in the pilot area. These primary porosity and intergranular permeability sand and gravel aquifers overlie the bedrock. Grain size distribution can be broad, with complex internal sedimentary architecture, but the deposits are characterised by high permeabilities and porosities. The majority of the aquifers are found along major rivers, although large glacial outwash fans also occur.

Land use over the karst aquifers is primarily dairying within enclosed fields, lesser tillage (crops), limited woodland, harvested peat, and relatively small built-up areas. Over the less productive aquifers, tillage dominates, with forestry in upland areas.

Groundwater from the Regionally important aquifers provides up to 90% of the public water supply in some counties within the region, and is important for agricultural and other private uses. These aquifers tend to occur in the lowlands, whereas the Locally important fissured aquifers tend to underlie higher ground. One groundwater level monitoring station from the poorer aquifers has been assessed as part of this study.

Four tools have been used to estimate the recharge values. These are the lumped parameter computer model Aquimod (Mackay *et al.*, 2014a), the transfer function-noise model Metran (Zaadnoordijk *et al.*, 2019), GARDENIA (Thiéry, 2013), and the spatially-distributed groundwater recharge model map (Hunter Williams *et al.*, 2013). Future climate scenarios are developed based on the ISIMIP (Inter Sectoral Impact Model Inter-comparison Project (www.isimip.org) datasets. The resolution of the data is 0.5° x 0.5° global grid and at daily time steps. As part of ISIMIP, much effort has been made to standardise the climate data (e.g. bias correction).

The long term average (LTA) historical recharge calculated for each borehole shows little correlation between AquiMod, GARDENIA and Metran. One observation station (Freshford) showed an order of magnitude difference between estimates. The smallest variation is a factor of two (Borrismore Creek). AquiMod and the Irish Groundwater Recharge model were consistent most frequently, although there wasn't a consistency of similarity/difference between models across all of the groundwater monitoring stations. The model which consistently calculates the highest recharge value is Metran which, in most cases, is roughly 10-20 mm/month greater than the next highest model. Most of the LTA recharge values calculated from GARDENIA boreholes are lower than those calculated from AquiMod, with two exceptions (Freshford and Vickerstown) which are both much higher than the recharge values from AquiMod.

These differences are perhaps not surprising, due to the different approaches and different catchment sizes modelled by AquiMod and GARDENIA, as well as the differences in how the models operate and how they calculate recharge. In the case of GARDENIA, it was difficult to find river flow data appropriate for the groundwater monitoring points used, and it might be that Irish catchments are heterogeneous on a scale that is too fine relative to the density of hydrometric data. Furthermore, due to time constraints within the study, the simplest model structures were used for AquiMod (1 layer) and GARDENIA (1 groundwater reservoir).

The difference between recharge estimates does pose a difficulty in deciding which is the 'right' value but, on the other hand, highlights the uncertainty in deriving recharge estimates and may also indicate where improvements in model set-up and hydrogeological representation are required.

Future recharge values were calculated using AquiMod, GARDENIA and Metran.

All three models show the greatest increase in recharge values observed across all boreholes when the 3°C max scenario data are used (excluding the anomalous projected values for Borrismore Creek, BMC), with the exception of Freshford (Metran) which shows a 10.4% decrease in recharge.

The greatest reduction in recharge values are observed in:

- AquiMod: the 3°C min scenario, with the exception of Freshford which displays a 5.3% increase in recharge. s.
- GARDENIA: the 3°C min scenario
- Metran: the 3°C min scenario, with values ranging from -4.0% to -22.7%.

Future estimates are discussed in this report using long term average recharge values. It is recommended to carry out further analyses of these outputs in order to understand the temporal changes in recharge values in future, especially over the different seasons. In addition, it is recommended that the values and conclusion produced from this work should be compared to those obtained from different studies that apply future climate data obtained from different climate models. Future climate change scenarios will be applied to the Irish Groundwater Recharge model.

2 INTRODUCTION

Climate change (CC) has already had widespread and significant impacts in Europe, which is expected to increase in the future. Groundwater plays a vital role for the land phase of the freshwater cycle and have the capability of buffering or enhancing the impact from extreme climate events causing droughts or floods, depending on the subsurface properties and the status of the system (dry/wet) prior to the climate event. Understanding and taking the hydrogeology into account is therefore essential in the assessment of climate change impacts. Providing harmonised results and products across Europe is further vital for supporting stakeholders, decision makers and EU policies makers.

The Geological Survey Organisations (GSOs) in Europe compile the necessary data and knowledge of the groundwater systems across Europe. In order to enhance the utilisation of these data and knowledge of the subsurface system in CC impact assessments the GSOs, in the framework of GeoERA, has established the project “Tools for Assessment of Climate change ImpaCt on Groundwater and Adaptation Strategies – TACTIC”. By collaboration among the involved partners, TACTIC aims to enhance and harmonise CC impact assessments and identification and analyses of potential adaptation strategies.

TACTIC is centred around 40 pilot studies covering a variety of CC challenges as well as different hydrogeological settings and different management systems found in Europe. Knowledge and experiences from the pilots will be synthesised and provide a basis for the development of an infra structure on CC impact assessments and adaptation strategies. The final projects results will be made available through the common GeoERA Information Platform (<http://www.europe-geology.eu>).

The specific TACTIC activities focus on the following research questions:

- What are the challenges related to groundwater- surface water interaction under future climate projections (TACTIC WP3)?
- Estimation of renewable resources (groundwater recharge) and the assessment of their vulnerability to future climate variations (TACTIC WP4).
- Study the impact of overexploitation of the groundwater resources and the risks of saline intrusion under current and future climates (TACTIC WP5).
- Analyse the effectiveness of selected adaptation strategies to mitigate the impacts of climate change (TACTIC WP6).

The present document reports the TACTIC activities in the Irish midlands and South-east pilot area undertaken by Geological Survey Ireland (GSI) as part of WP4.

WP4 is divided into seven tasks that cover the following activities: Review of tools and methods and identification of data requirements (Task 4.1), identification of principal aquifers and their characteristics aided by satellite data (Task 4.2), recharge estimation and its evolution under climate change scenarios in the principal aquifers (Task 4.3), analysis of long-term piezometric time series to evaluate aquifer vulnerability to climate change (Task 4.4), assessment of subsidence in aquifer systems using DInSAR satellite data (Task 4.5),

development of a satellite based net precipitation and recharge map at the pan-European scale (Task 4.6), and tool descriptions and guidelines (Task 4.7).

Two different works are presented in this report and they are related to Task 4.3 and Task 4.4.

The pilot area is in the SE part of Ireland, and comprises the river basins of the Suir, Nore, Barrow and Slaney rivers, as well as a number of smaller coastal rivers. It also incorporates small parts of other river catchments where certain aquifers extend over catchment boundaries.

The main aquifers of interest within the pilot area are (1) the diffusely karstified limestone aquifer and (2) the extensive sands and gravels aquifers. The karst aquifers occupy the valleys and lowlands and are used for several major public drinking water abstractions, for agriculture, and for industrial abstractions. There are also two lead-zinc mines in the aquifer that have been closed, and groundwater levels are now rebounding. Sands and gravels are mainly found along the major rivers, but also occur as extensive 'domes'. They are used for public drinking water supplies and for private abstractions. Groundwater from these principal aquifers supports river flows to a significant extent.

Other aquifers, both major and minor, are however also of interest for representativity for the rest of Ireland. The other major aquifers in the area include a fissured volcanic rock aquifer and a productive dual porosity sandstone aquifer. The remainder of the area is underlain by poor and locally important fissured aquifers. In general, the karst limestone aquifers are coincident with the valleys, and the glacio-fluvial sand and gravel aquifers lie along the principal rivers. The higher ground is formed by more resistant bedrock that typically comprise poor or only locally important aquifers.

The southeast of Ireland is a relatively dry and warm region within the Irish cool temperate climatic zone. Annual mean rainfall is 800–1000 mm in the lowlands, which is the area occupied by the main aquifers of interest in the study area. The annual potential evapotranspiration varies spatially between 450 mm and in excess of 500 mm. Therefore, effective rainfall is (for Ireland) low, at approximately 250-400 mm/yr.

The area is, therefore, one for which concerns currently exist about water resources availability, and it anticipated that this area will become progressively water stressed under future climate change scenarios (e.g. Hunter Williams and Lee, 2007; Ball, 2010).

The work undertaken in the pilot area will build on the study by Tedd *et al.* (2012), which examined groundwater level variations to ascertain aquifer response to rainfall, and tried to determine whether there was evidence of climate change impacts. It is hoped that analysis of data and inferences and results from the pilot area will be used to improve the current Irish national groundwater recharge map (Hunter Williams *et al.*, 2013). As part of the study, an updated 30 year average groundwater recharge map using current recharge coefficients was produced, which will be used for climate change scenarios in the future.

3 PILOT AREA

3.1 Site description and data

The pilot area is in the SE part of Ireland, and comprises the river basins of the Suir, Nore, Barrow and Slaney rivers, as well as a number of smaller coastal rivers (**Figure 1**). It also takes in a small area of the adjacent river catchments in some places where limestone aquifer units cross catchment boundaries in the north of the area. The Suir, Nore and Barrow rivers converge into Waterford estuary; the Slaney river flows into Wexford estuary.

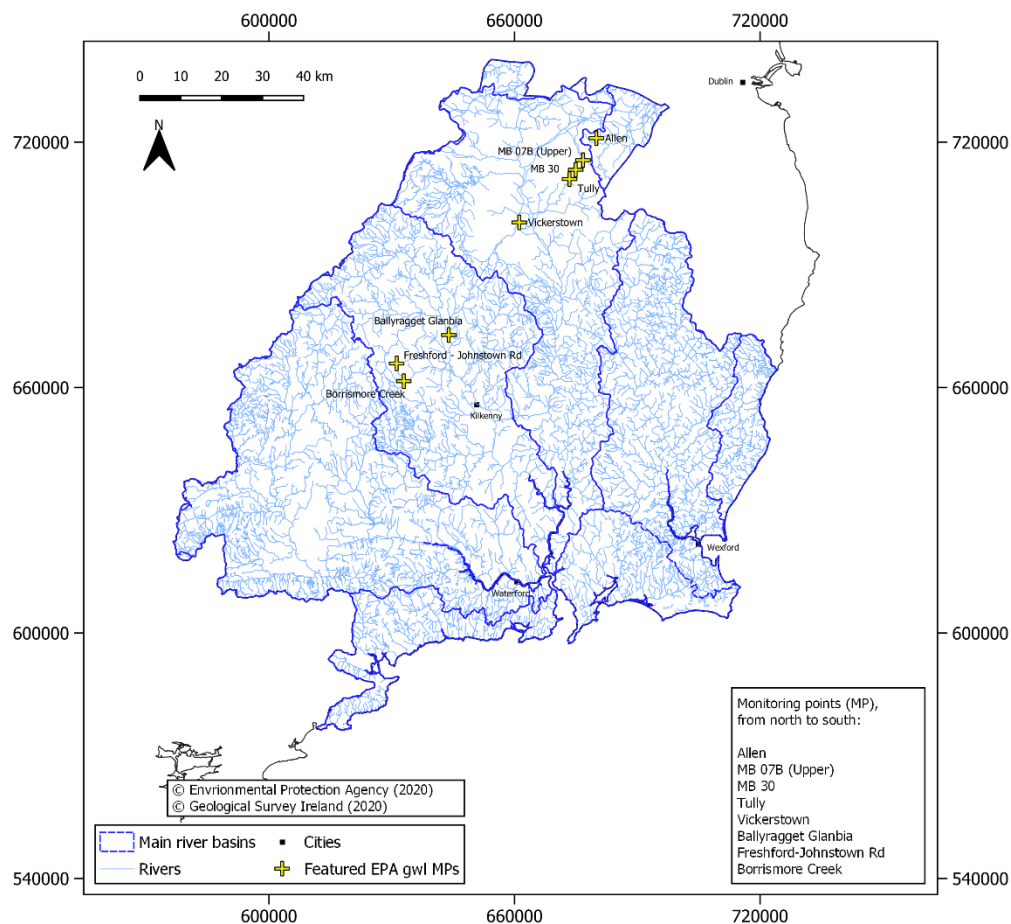


Figure 1. Pilot area in the SE of Ireland

The study area is bounded to the NE, NW and SW by mountain ranges (elevation up to 920 m aOD (metres above Ordnance Datum)), and to the E, SE and S by the coast. Within the study area the Castlecomer Plateau and the Slieveardagh Hills (up to 600 m aOD) separate two NE–SW-trending lowlands areas, which are occupied by karst limestone and glacio-fluvial gravel aquifers.



Within the pilot area as a whole, the principal aquifers of interest are the karstified (and sometimes dolomitised) limestones that occupy the lowland areas, and the extensive sands and gravels that follow the main rivers, and also occur as topographic domes (**Figure 2**).

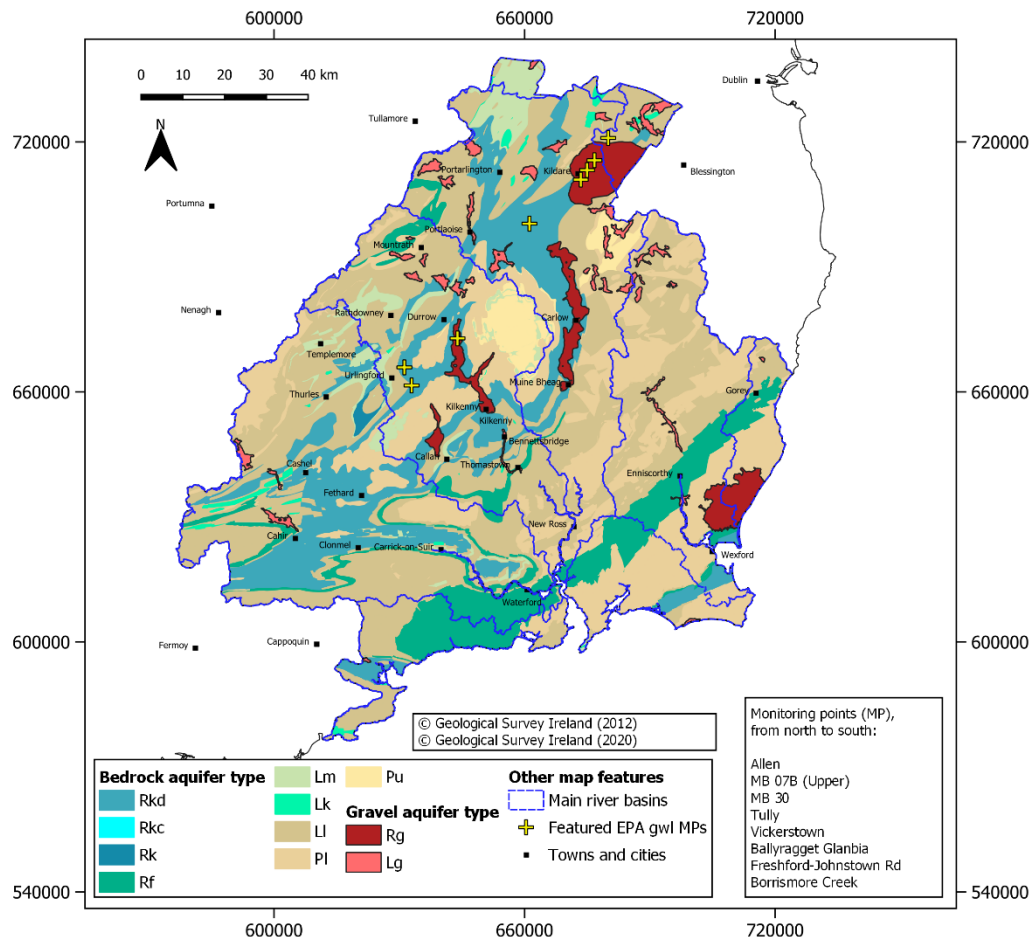


Figure 2. Aquifers in the pilot area and locations of selected observation boreholes. The main aquifers of interest are the karst (Rk, Rkc, Rkd) and extensive sand and gravel (Rg) aquifers.

3.1.1 Index boreholes in the pilot area

Diffusely karstified limestone aquifers are important in the midlands and SE, and supply the whole of Co. Laois public water supply network. They are also important for the neighbouring counties of Kilkenny and Carlow. The aquifer comprises pure, bedded limestones that have been folded and fractured. These fissures have been enlarged through the solution of limestone by percolating recharge and flowing groundwaters. Whilst some conduits have developed and caves are known, the area is considered to be ‘diffusely’ karstified, such that groundwater flow pathways are well-distributed through the rock mass. Some of the limestones have also been dolomitised, which has further increased permeability and porosity.



The fissured limestones have only secondary, fissure porosity and permeability. Dolomitisation has introduced spatially limited secondary intergranular porosity and permeability. This aquifer extends from the north of the pilot area southwards and southwestwards. The subcrop of the aquifer splits around the higher ground of the Castlecomer plateau. However, it is thought that the aquifer is continuous through the syncline below the younger rocks of the plateau.

In contrast to bedrock aquifers, Quaternary glacio-fluvial sand and gravel aquifers provide an opportunity for intergranular groundwater flow. There are five regionally important sand and gravel aquifers in the study area, including the c. 200 km² Mid-Kildare Sand and Gravel Aquifer, which extends into the north-east of the study area and is one of the most extensive sand/gravel bodies in Ireland, and the c. 55 km² Nore River sands and gravels. Aquifer thickness varies from 20-40 m, but the mid-Kildare gravel can be significantly thicker. The Nore Gravels can be variable in thickness, with bedrock 'towers' poking through. The sediments vary considerably over short distances but are dominated by gravel and sand. Sorting can be poor or good, and there can also be clay horizons.

The SE region has been relatively well-studied over the years, including by E. Daly (1978, 1980, 1981, 1982, 1990, 1993, 1994), Cawley (1990) and Tedd *et al.* (2012, 2013). Studies included data collection, groundwater system conceptualisation, interpretation of groundwater levels, hydrometeorological studies, and preliminary inferences about climate change impacts. There are also almost 100 source-specific studies for groundwater-fed drinking water supplies (public schemes and group schemes).

The study area has a number of observed groundwater level data obtained from some of the number of boreholes that have been drilled in the area. In addition to the important role these groundwater level data can play in calibration of numerical models, they can be also used to undertake statistical analysis and apply lumped models. This allows better understanding of the hydrogeological behaviour of the aquifer, the reconstruction of past groundwater levels to study past drought and flooding events, making short-term groundwater level predictions, and studying the impact of climate change. The groundwater level observation boreholes analysed in this study are summarised in **Table 1** and are shown on **Figure 1** and subsequent maps. The objectives of the analyses are to improve understanding of groundwater recharge mechanisms and timing, and to begin to make predictions about the variation of groundwater recharge under the future climate conditions.

The actively monitored boreholes are part of the Environmental Protection Agency (EPA) groundwater monitoring network. The historic borehole data are from previous Geological Survey Ireland studies, some of which were incorporated into the active EPA network.

Table 1: Details of Groundwater Level Monitoring point, meteorological stations and surface flow gauging stations, and other catchment details

Groundwater level Monitoring Point						Land Use (CORINE 2018)	Precipitation			Potential Evapotranspiration			Evaporation (Metran only)		River Discharge/Flow		
Name	Record Length	Bore- hole depth (m bgl)	Depth to groundw ater (m bgl)	Aquifer Type	Aquifer Vulnera- bility		Station Name	Distance to 1 st Station (km)	Record Length	Station Name	Distance to Station (km)	Record Length	Station Name	Record Length	Station Name	Distance to Station (km)	Record Length
Allen	Jan 1997 – Jul 2020	37.4	1.55 - 3.055	Poorly productive fissured	Moderate & Low	Discontin- uous urban fabric	Naas (Osberstown)	7.2	May 2008 – Jul 2020	Casement	25.6	Jan 1967 – Jan 2021	Casement	May 2008 – Jul 2020	Osberstown House	7.6	May 2009 – Dec 2020
Ballyragget Glanbia	Mar 2008 – Oct 2020	18	2.2 - 5.61	Sand & Gravel and karst	High & Extreme	Pastures	Parknahown Cullahill, Durrow, Ballyroan	9.8	Nov 1981 – Aug 2020 (all same)	Oak Park	30.1	Jan 2008 – Sep 2020	Oak Park	Mar 2008 – Dec 2020	John's Bridge	18.1	Oct 1971 – Dec 2017
Borrismore Creek	Apr 1975 – Aug 2020	36	9.02 - 18.86	Regionally important karst	Extreme & High	Complex cultivation patterns	Parknahown Cullahill, Drangan	12.5	Apr 1975 – Aug 2020 (all same)	Kilkenny, Oak Park	44.4	Jan 1970 – Jan 2019	Kilkenny, Oak Park	May 1975 – Aug 2020	Ballinfrase	12.1	Jul 2001 – Mar 2021
Freshford – Johnstown Rd	Apr 2008 – Aug 2020	13.5 (sump at 12.3 m)	10.60 - 12.31	Regionally important karst	Moderate, High & Extreme	Pastures	Parknahown Cullahill	8.6	Apr 2008 – Aug 2020	Oak Park	44.3	Jan 2008 – Sep 2020	Oak Park	Apr 2008 – Aug 2020	Durrow Ft Bridge	14.9	Jan 1972 – Oct 2018
MB 07B Upper	May 2008 – Jul 2020	Un- known (<48)	17.95 - 19.38	Sand & Gravel	High	Pastures	Naas (Osberstown)	11.5	May 2008 – Jul 2020	Casement	30.7	Jan 1967 – Jan 2021	Casement	May 2008 – Jul 2020	Rathangan	10.3	Jan 1999 – Jun 2020
MB 30	Apr 2008 – Jul 2020	24	5.53 - 9.67	Sand & Gravel	High	Natural grasslands	Naas (Osberstown)	14.1	Apr 2008 – Jul 2020	Oak Park	34.3	Jan 2008 – Sep 2020	Oak Park	Apr 2008 – Jul 2020	Japanese Gardens	2.9	Jan 1982 – Sep 2020
Tully	Jun 2008 – Jul 2020	9	0.27 - 1.17	Sand & Gravel	High	Pastures	Naas (Osberstown), Casement	16.6	Jun 2008 – Jul 2020 (all same)	Casement	32.1	Jan 2008 – Sep 2020	Casement	Jun 2008 – Jul 2020	Japanese Gardens	0.2	Jan 1982 – Sep 2020
Vickerstown	Oct 1995 – Sep 2020	25	2.35 - 6.4	Regionally important karst	High & Moderate	Pastures	Athy (Chanterlands) , Castledermot Kilkea House	10.4	Jul 1993 – Sep 2020, Jan 1990 – Dec 2020	Kilkenny, Oak Park	24.7	Jan 1970 – Jan 2019	Kilkenny, Oak Park	Jan 1990 – Dec 2020	Derrybrock	1.3	Feb 1980 – Oct 2020



3.1.2 Topography

The study area is bounded to the NE, NW and SW by mountain ranges (elevation up to 927 m aOD (metres above Ordnance Datum)), and to the SE by the coast. Within the study area the Castlecomer Plateau and the Slieveardagh Hills (up to 600 m aOD) separate two NE–SW-trending lowlands areas. The main lowlands of the study area are:

- to the west of the Castlecomer Plateau and Slieveardagh Hills, which lie typically between 130 and 100 m aOD;
- to the east of the Castlecomer Plateau and the Slieveardagh Hills, which lie typically between 90 and 30 m aOD; and
- coastal (to the east of the Blackstairs Mountains), which lie typically between 60 m aOD and sea level.

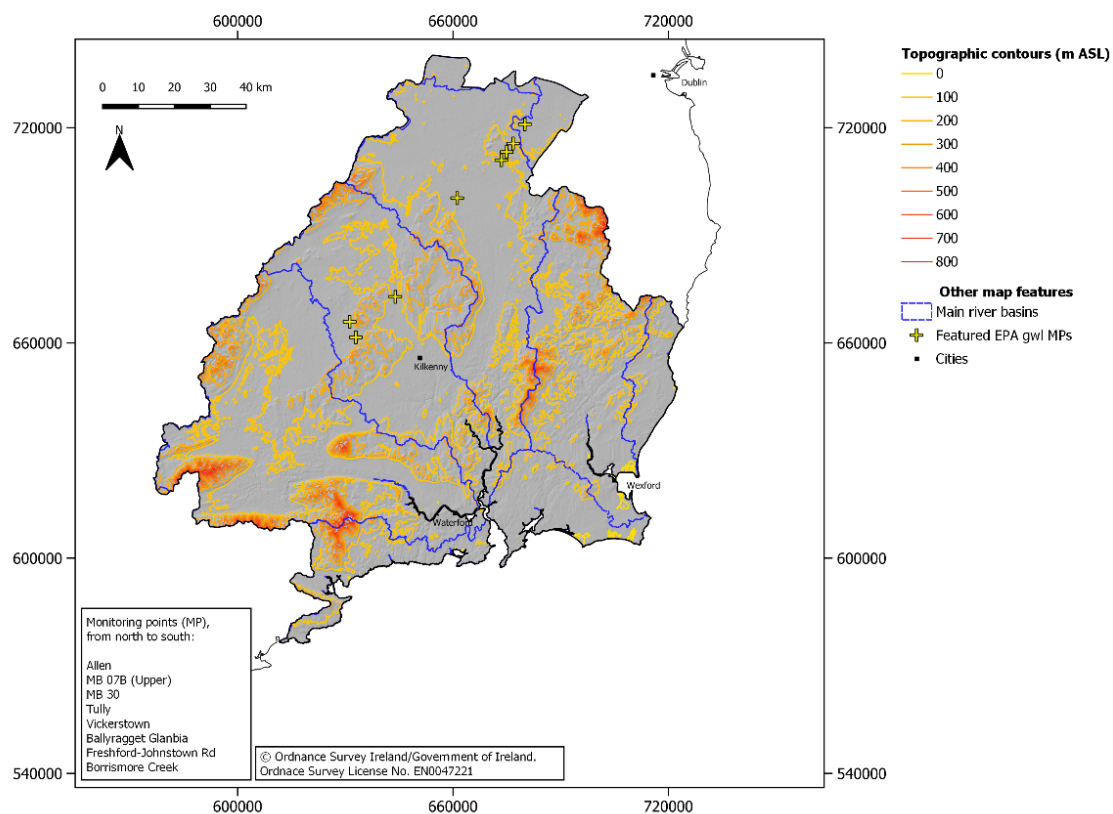


Figure 3. Topography over the pilot area

3.1.3 Landuse and Climate

Landuse

Land use includes enclosed fields, woodland, open land, and built-up areas. There are also two closed lead-zinc mines (one of which is planning to re-open). Much of the land over the diffusely karstified limestones is in agricultural use, while there are smaller areas of



urbanisation, including residential or commercial developments. There are also one-off houses, with their own septic systems, either on scattered farms or as ribbon developments. Farming activities above the limestone aquifers are dominated by intensive dairying, with lesser amounts of tillage. Over sands and gravels, sheep grazing is common, or drystock. In non-limestone areas, farming includes tillage, dairying and drystock.

Landuse data can be extracted from the Corine map (CLC2018, EPA 2018) specify the model parameters that control evapotranspiration.

Rainfall

On a national scale, the pilot area is a relatively dry region. The Agroclimate Atlas of Ireland (Collins and Cummins, 1996) shows the annual mean rainfall to be between 800 and 1,000 mm in the lowlands of the SE Region, 1,000 and 1,250 mm in upland areas (200– 600 m), and in excess of 2,000 mm in mountainous areas (greater than 600 m). Precipitation values in excess of 1,200 mm are typical over most of the rest of the country.

Rainfall is measured by Met Éireann at 61 rainfall stations throughout the pilot area. There are two synoptic stations within the SE region: Oak Park (which replaced Kilkenny in March 2008) and Johnstown Castle (which replaced Rosslare in March 2008). At synoptic stations, meteorological elements, such as air temperature, rainfall, humidity, vapour pressure, wind speed, wind direction and atmospheric pressure, are recorded on an hourly basis. Daily evaporation, potential evapotranspiration (PE) and soil moisture deficits (SMDs) are calculated for these stations (<http://www.met.ie>). Spatially distributed rainfall data are available at daily time steps starting from 1961 to 2018 (Met Éireann). These are on a 5 x 5 km grid. While the size of this time step is too coarse to represent storm events for hydrological analysis, it is fine enough to calculate recharge values to drive groundwater models.

Projected (future) values of rainfall data and PE and AE are also available through the work of Met Éireann and ICHEC (Irish Centre for High End Computing), e.g. Nolan (2015). These data will be available for use for the estimation of projected (future) recharge values. It was not possible to incorporate them within this study for various reasons.

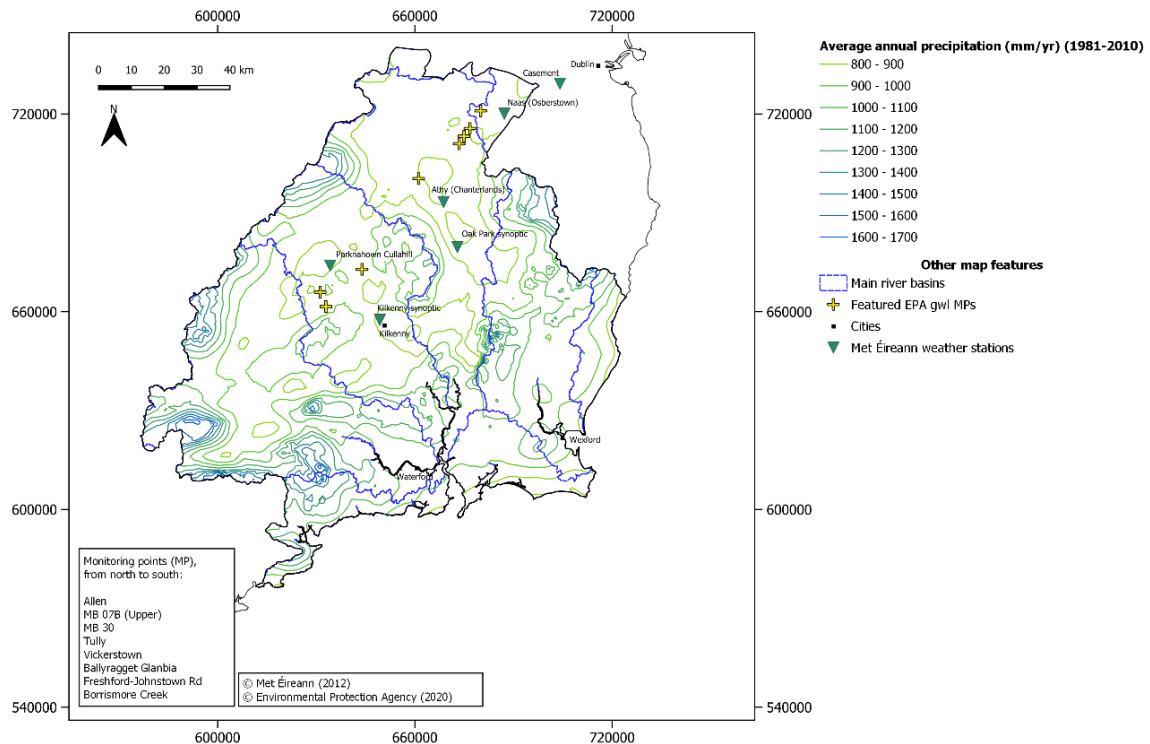


Figure 4. Spatial distribution of rainfall in the SE region

Potential evaporation

The Agroclimate Atlas of Ireland (Collins and Cummins, 1996) shows the annual PE in the SE region varies spatially between 450 mm and in excess of 500 mm. Potential evapotranspiration is relatively stable throughout the country, increasing with proximity to the coast. Calculated PE is available for the synoptic weather stations at Kilkenny and Oakpark. PE is minimum in winter, increasing during the spring to a maximum in the summer, before declining in the autumn. Grass growth typically starts around the start of March, and can continue into October, although annual variations in climate will impact this.

Average monthly PE values calculated and reported by Tedd *et al.* (2012) for the Kilkenny synoptic station range from approximately 5-10 mm in December and January, to 75-85 mm in June and July. Estimated average monthly AE ranges from 5-10 mm (December and January) to 60-75 mm in summer. The corresponding annual average PE ranges from 448 – 535 mm/yr, and AE from 421 – 491 mm/yr. Note that these are ranges due to different sources of information, estimation methods, and reference time periods.

Daily potential (reference) evapotranspiration and Actual evapotranspiration are available on a km-scale grid for the period 1981 onwards (Werner, Nolan and Naughton, 2019). These are available for a reference crop and for different soil classes.



Similar to rainfall data, potential and actual evaporation data from Met Éireann and ICHEC will be available in the future to be used to run simulations to calculate future recharge values.

3.1.4 Geology

The study area is underlain by extremely heterogeneous strata, principally of Lower Palaeozoic, Devonian and Carboniferous age (**Figure 5**), with extensive, and spatially variable, overlying subsoil deposits. The majority of bedrock geological information comes from the GSI reports accompanying the GSI's 1:100,000 geological map sheets covering the area (Tietzsch-Tyler et al., 1994; Archer et al., 1996) and from the hydrostratigraphic units map (GSI, 2005a).

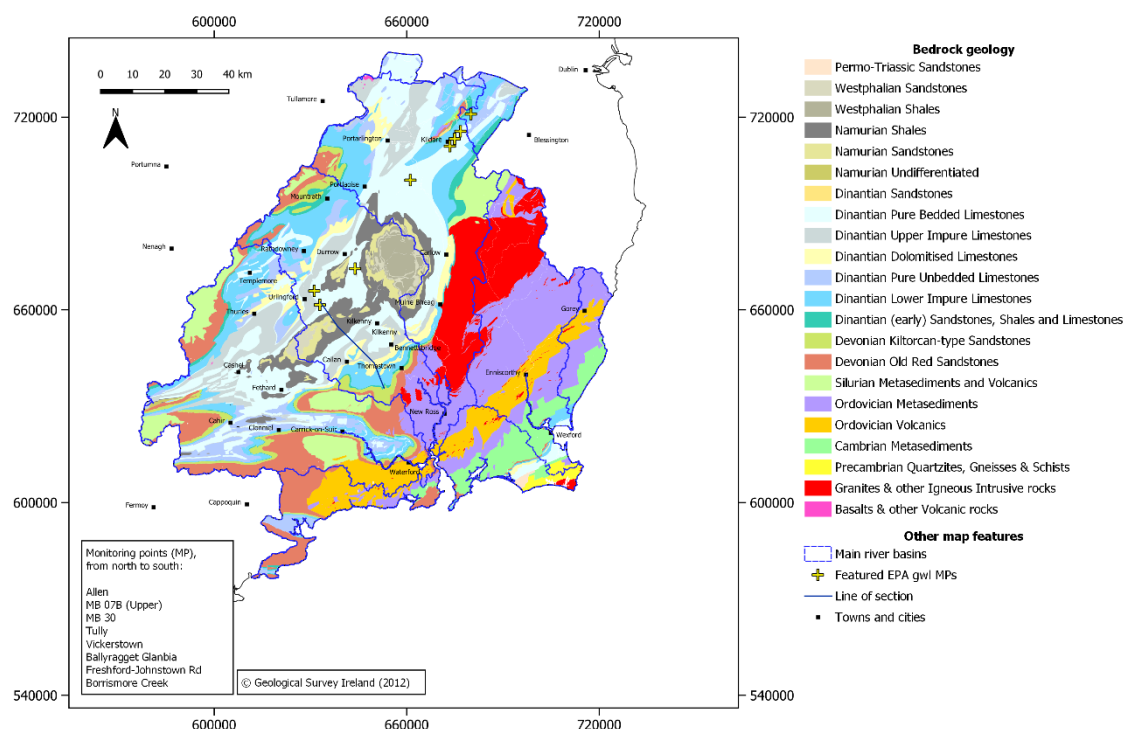


Figure 5. Generalised bedrock geology (hydrostratigraphic units) of the South Eastern region. Cross-section shown in line of section on this map (blue) is in Figure 6.

Lower Palaeozoic strata outcrop in the east of the study area and underlie the majority of Counties Wexford, Waterford and Wicklow and the east of Counties Carlow, Kilkenny and Kildare. They are also exposed via inliers in the Galtee, Slieve Bloom and Slievenamon Mountains. The deposits comprise metasedimentary and volcanic rocks associated with the evolution of the Iapetus Ocean. They are folded with a north-east to south-west trend and are extensively faulted; therefore, they are typically steeply dipping and include overturned beds (Archer et al., 1996). The Ordovician volcanics are well-fractured and form a major aquifer. Late Devonian-early Carboniferous dual porosity sandstones skirt the higher ground. They have a relatively limited outcrop area, but extend below overlying strata as confined systems. The remainder of the Lower Palaeozoic rocks are categorised as locally important or poor aquifers.



Lower Carboniferous strata comprise:

- impure and shaley limestones (the early Sandstones, Shales and Limestones; Lower Impure Limestones and Upper Impure Limestones rock unit groups (see **Figure 5**), which form poorly productive aquifers in general, and;
- pure limestones (Pure Unbedded Limestones rock unit group, also known as the Waulsortian, Pure Bedded Limestones rock unit group, and Dolomitised Limestones rock unit group), which generally form karstified regionally important aquifers.

There are a few exceptions, including: Waulsortian limestones don't always karstify significantly, and can be poorly productive aquifers; the early Carboniferous strata in some areas are dominated by calcareous sandstone, which does form a principal aquifer; impure limestones can be dolomitised and become more porous and permeable.

Upper Carboniferous strata form the core of a syncline and underlie the high ground in the centre of the study area.

3.1.5 Hydrology

The Rivers Suir, Barrow and Nore rise in the Slieve Bloom to Silvermines Mountains. The three rivers – known as the 'Three Sisters' – take different courses before converging in the Waterford Estuary. The River Slaney rises in the Wicklow Mountains and flows south-east into the Wexford Estuary (see **Figure 1**). The EPA and other organisations monitor the flow of rivers at 134 hydrometric stations within the river catchments. Only a subset of these is for flow as well as level, however. Baseflows are high where rivers have crossed the major karst limestone aquifers or the extensive glacio-fluvial sand and gravel aquifers.

3.1.6 Hydrogeology

The solid geology underlying the SERBD is heterogeneous. In general, alteration, cementation and intensive structural deformation means that groundwater flow is through secondary porosity and dominated by fracture flow. In a typical fractured hydrogeological system, the occurrence of open water-bearing fractures is greatest at shallow depths. Typically, hydraulic conductivity declines with depth as fractures become tighter and less common. Therefore, groundwater flow paths are likely to be shallow, predominantly in the upper layer of the aquifer with enhanced weathering and open fractures (Robins and Misstear, 2000). These types of aquifers typically have limited yields, transmissivities and storage, and are classified as Locally important and poor aquifers (LL, PL and Pu).

The karstified and dolomitised limestones have permeable zones at greater depths, relating to earlier periods of alteration. This is in addition to solutionally-enlarged fissures and development of cavities from recrystallization. Consequently, they are classified as regionally important aquifers (**Figure 2**). The regionally important aquifers in the study area are (GSI, 2006):

- Ordovician volcanics (Rf);
- Devonian to Early-Carboniferous Kiltorcan Sandstone Aquifer (including sandstones of the overlying Porter's Gate Formation) (Rf)



- Dinantian Dolomitised Limestones (Waulsortian, Butlersgrove and Milford Formations and equivalent horizons) (Rkd);
- Dinantian Karstified Limestones (Ballyadams and Clogrennan Formations) (Rkd); and
- Quaternary Sand and Gravel aquifers (Rg and Lg).

The aquifers of principal interest in the pilot area comprise:

(1) a north-south/NE-SW oriented band of limestone that occupies the valleys either side of the upland Castlecomer Plateau, whose younger rocks form the core of a syncline.

The pure limestones form a highly transmissive but low storativity aquifer. Fractures are solutionally-enhanced, leading to a distributed network of enlarged fissures. Conduits and caves are known, but are not thought to dominate groundwater flow. Well yields range from 30 – 3,000 m³/d, and are typically 250-1,000 m³/d. Transmissivities are on the order of 20-2,000 m²/d, generally 200-250 m²/d. Specific yields are very low, ranging from 0.005 to 0.05. Where dolomitised, porosity and storage is at the upper end of this range.

The karstified/dolomitised limestones are typically overlain by medium permeability glacial tills or sands and gravels. Groundwater within the outcrop part of the limestone is mostly under unconfined conditions. Where the aquifer is overlain by Namurian and Westphalian bedrock, it is confined. The nature of this part of the aquifer is not well-known, and it is not clear to what extent porosity and permeability are developed compared to the unconfined portions.

(2) extensive glacio-fluvial sands and gravels that form highly transmissive and high storativity aquifers. Well yields are in the range 250-1,000 m³/d. Transmissivities are on the order of 200–2,000 m²/d, typically 250–450 m²/d depending on the sorting and thickness of the aquifer. Specific yields are typically 0.12–0.19. There are five large sand and gravel aquifers in the study area. The two aquifers containing groundwater level monitoring boreholes assessed in this study are the mid-Kildare (Curragh) and Nore River gravels. The mid-Kildare aquifer can reach thicknesses of >100 m, but is mostly 20-40 m thick. It is generally unconfined, although very localised confined conditions exist under fen peats. The Nore River gravels are typically 10-30 m thick and are unconfined. The other three gravel bodies are typically unconfined, although where the aquifer is overlain by very thick Irish Sea tills, it is confined.

3.1.7 Groundwater levels

Groundwater level variation is influenced by the level of subsoil cover and the position of the monitoring point relative to the catchment (i.e. in elevated or interfluvial areas, or adjacent to rivers). Within the pilot area, in elevated areas with little subsoil, recharge can reach the saturated zone very rapidly through fractures and solutionally-enlarged fissures. Groundwater levels in fractured and karstified bedrock aquifers can vary by up to 40 m seasonally, although this is exceptional, and annual variations are more typically 10-15 m in these settings. Where there is subsoil covering the aquifer, this process is attenuated and slowed down. Groundwater level variation adjacent to rivers shows annual variations of around 2-3 m, typically (**Figure 6**), and are also much shallower. Groundwater level ranges in the sand and gravel aquifers are on the order of 2-3 m seasonally.



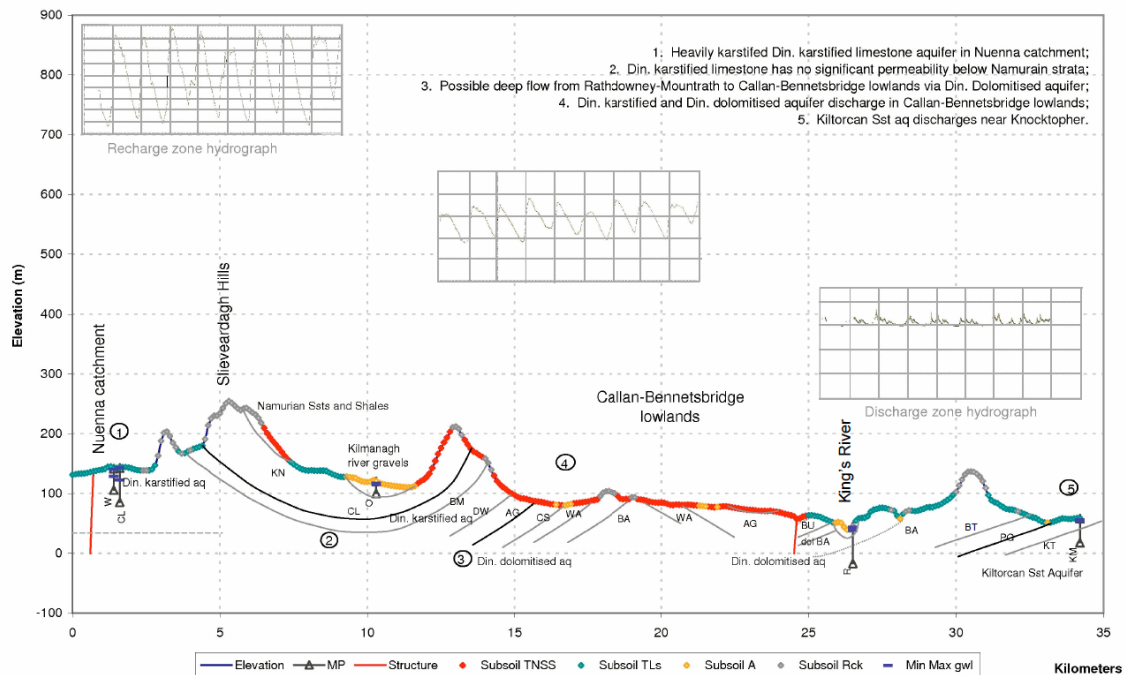


Figure 6. Schematic conceptual model cross-section through the southeastern region. From Tedd *et al.* (2011). Cross-section is oriented from NW to SE and line is shown on Figure 5.

3.2 Climate change challenge

The European Environment Agency map describes the expected climate change across the different areas in Europe as shown in **Figure 7**. This indicates that a shortening of recharge season, potentially resulting in aquifers becoming more vulnerable to droughts if rainfall fails in one or two months rather than a prolonged dry winter as can occur now.

The main climate challenge for water resources managers and stakeholders is to assess the risk of future drought events. This requires detailed assessment of the variation of resources at regional and local scales rather than national or continental scales.

Higher winter rainfalls and groundwater recharge will result in higher groundwater levels, if overlying subsoils are sufficiently permeable to allow the recharge through. This will, in turn, lead to higher discharges of groundwater in winter and spring. The problems that will arise relate to the capacity of the combined groundwater surface water system downgradient of the recharge area. If the down gradient system is not able to take the higher groundwater flow rates, then there will be flooding. In the Southeast region, this is not expected to be extensive. However, increased magnitude and length of groundwater fluxes will lead to greater baseflow, which may exacerbate river flooding extents and durations. Conversely, drier than usual



summers will adversely impact summer river flows where they cross poorly productive aquifers, and baseflows are generally lower.

High groundwater flow rates through karstified aquifers may result in an increase in turbidity and contamination. This may occur in spring waters used as a water supply, and also in inadequately constructed boreholes.

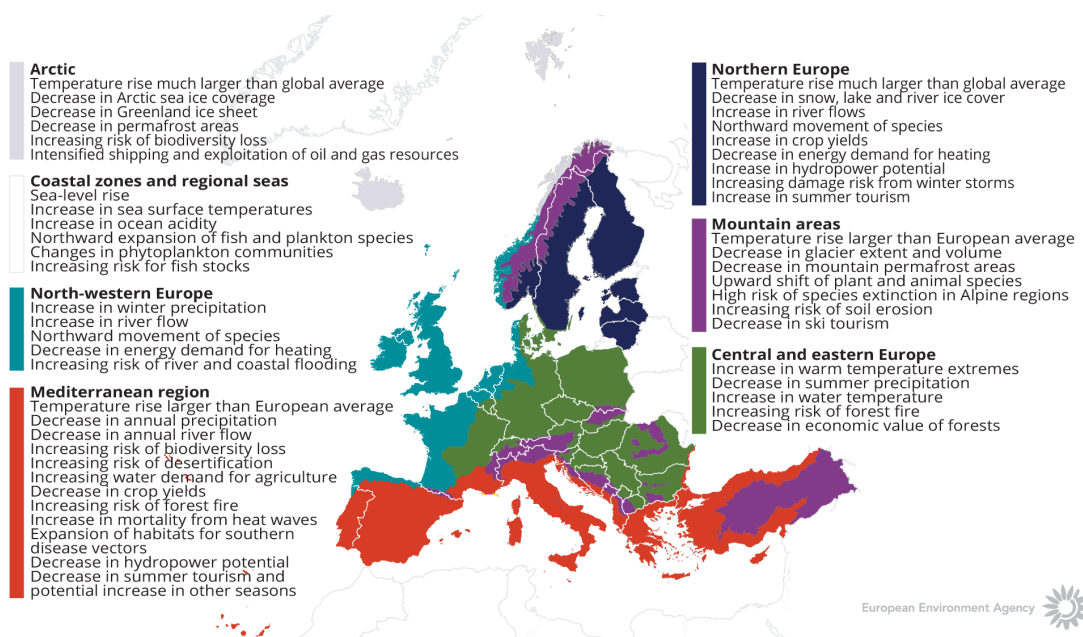


**Figure 7. How climate is expected to change in Europe.
The European Environment Agency map**

4 METHODOLOGY

4.1 Methodology and climate data

4.1.1 *AquiMod*

AquiMod is a lumped parameter computer model that has been developed to simulate groundwater level time series at observational boreholes (Mackay et al., 2014a). It is based on hydrological algorithms that simulate the movement of groundwater within the soil zone, the unsaturated zone, and the saturated zone. The lumped models neglect complexities included in distributed groundwater models but maintain some of the fundamental physical principles that can be related to the conceptual understanding of the groundwater system (Mackay et al., 2014b).

The primary aim of AquiMod is to capture the behaviour of a groundwater system through the analysis of the available groundwater level time series. Once calibrated, the model can be run in predictive mode and be used to fill in gaps in historical groundwater level time series and to calculate future groundwater levels. In addition to groundwater levels, it also provides predictions of historical and future recharge values and groundwater discharges.

The mathematical equations that are used to simulate the movement of groundwater flows within the three modules are detailed in **Appendix C**. The model uses rainfall and potential evaporation time series as forcing data. These are interpreted by the soil module representing the soil zone. The soil module calculates the rainfall infiltration and passes it to the unsaturated zone module. This module delays the arrival of the infiltrating water to the saturated zone module. The latter calculates the variations of groundwater heads and flows accordingly.

AquiMod is calibrated using a Monte Carlo approach. It compares the simulated and observed groundwater level fluctuations and calculates a goodness of fit. The AquiMod version used in this work employs the Nash Sutcliffe (NSE) to assess the performance of the model. The user sets a threshold value to accept all the models that perform better than the specified threshold. The possibility of producing many models that are all equally acceptable, allows the user to interpret the results from all these models and calculate uncertainty.

The recharge values calculated from AquiMod are those that reach the aquifer system and drive the groundwater levels. Thus, it is assumed that these are the actual recharge values as defined in Karlsson et al. (2020).

4.1.2 *GARDENIA*

GARDENIA is a lumped hydrological model for the simulation of relationships between series of stream or spring flow data at the outlet of a watershed, and/or groundwater level data at an observation well situated in the underlying aquifer and the rainfall received over the corresponding watershed. Withdrawals by pumping groundwater can be considered if necessary.

GARDENIA enables the user to set a hydrological balance for the basin: actual evapotranspiration, runoff, infiltration, and recharge. The hydrological balance can be used for the evaluation of natural groundwater recharge of aquifers. GARDENIA gives the extension of river flow, groundwater level or recharge data over a long period for which precipitation and potential evaporation data are known. These long river flows and/or groundwater level series can then be used to:

- forecast river flows or groundwater levels for civil engineering applications;
- study particular events such as groundwater flooding or the occurrence of droughts;
- quantify the water balance components of a catchment at a pre-defined time-step (varying from one day to one month) for water resource evaluation or as input for a distributed groundwater model; and
- study the impact of climate change.

The climate data required for the model are:

- A continuous series of rainfall data.
- A continuous series of potential evapotranspiration data (PET). PET values can be either calculated from information related to sunshine duration, air temperature and relative humidity data, or it can be obtained directly from Meteorological offices.

One or two series of observations can be considered: river flows at the basin outlet and/or representative groundwater levels at an observation well located in the basin. The model can take into account impact of groundwater or river abstraction.

These different series of data must at a regular time step: daily, 5 days, 10 days, or monthly. All the series should refer to the same period. The time step of each series is not necessarily identical (e.g. daily rainfall and monthly PET).

The modelling of the relationships between rainfall and river flows and/or rainfall and groundwater levels includes a minimum of 4 to 6 lumped parameters (soil capacity, recession times, etc.) representative for a basin or a homogeneous unit within the basin. The software is executed in calibration phase first where model parameters are optimized automatically. The user has to select an objective function to evaluate model efficiency. This is usually dependent on the type of the investigated problem.

The computer code GARDÉNIA (modèle Global A Réservoirs pour la simulation des Débits et des Niveaux Aquifères) is a lumped hydrological model for watersheds. It uses time series of meteorological data (rainfall, potential evapotranspiration) recorded or calculated at a catchment to calculate:

- the river flows at the outlet of a river (or source) basin; and / or
- the groundwater levels at a borehole drilled in the underlying aquifer.

The effects of pumping or of a pumping group all located in the watershed can be taken into account. Calculations can be performed at a daily time step, decadal (ten days) or monthly. It is possible to take into account the snow melting process.

The modelling of the relationships between the rainfall and river flows and/or rainfall and groundwater levels includes 4 to 6 lumped parameters (soil capacity, recession times, etc.) representative for a basin or a homogeneous unit within the basin. These parameters are optimized using rainfall and river flow (and/or groundwater level) data over same observation period. The software under control of the user does this calibration phase of the model automatically.

After completion of the calibration, GARDENIA enables:

- The calculation of a hydrological water balance for the basin including actual evapotranspiration, runoff, infiltration, recharge (some terms can be used as input data in a discretized groundwater model). The hydrological water balance can be used for the evaluation of the renewable groundwater resources, mainly the groundwater recharge, of aquifers.
- The prediction of river flows, groundwater levels or recharge estimates over a historical or a future period for which precipitation and potential evaporation data are known. These projected river flow and/or groundwater level series can then be used for:
 - the forecasting of river flows or groundwater levels for the design of structures;
 - the study of particular events such as the rise of groundwater levels (flooding) or the occurrence of droughts; and
 - the study of the impact of climate change.

In addition to the possibility of estimating the different elements of the hydrological cycle (infiltration, evapotranspiration, runoff), GARDENIA allows the characterization of the hydraulic characteristics of the catchment through the calculation of the different runoff components (fast, slow and very slow components).

4.1.3 Metran

Metran applies a transfer function-noise model to simulate the fluctuation of groundwater heads with precipitation and evaporation as independent variables (Zaadnoordijk et al., 2019). The modelling approach consists mainly of two impulse functions and a noise model. The first impulse function is used for convolution with the precipitation to yield the precipitation contribution to the piezometric head. The second is for evaporation which is either a separately estimated function, or a factor times the function used for precipitation. The noise model is a stochastic noise process described by a first-order autoregressive model with one parameter and zero mean white noise. Further information about the model is given in **Appendix B** with the model setup shown in the Figure D1.

Metran allows the addition of other processes affecting the behaviour of the groundwater heads, for example pumping or the presence of surface features such as rivers. The contributions from these processes are added to the deterministic part of the model.

Metran has been designed to work with explanatory series that have a daily time step. However, it has been adapted so that other time step lengths can be applied. However, the explanatory variables must still have a constant frequency.

The model is calibrated automatically. However, the model uses two binary parameters, Regimeok and Modok, to judge a resulting time series model. Regimeok cross-examines the explained variance R^2 (> 0.3), the absolute correlation between deterministic component and residuals (< 0.2), and the null hypothesis of non-correlated innovations (p value > 0.01). If all these criteria are satisfied, Regimeok returns a value of 1 indicating highest quality. Modok also cross-examines the explained variance R^2 (> 0.1) and the absolute correlation between deterministic component and residuals (< 0.3) as well as the decay rate parameter (> 0.002) and if all these criteria are satisfied, it is given a value of 1. If Modok = 1 and Regimeok = 0, the model is still considered acceptable. If both these parameters are 0, the model quality is insufficient, and the model is rejected.

Metran's time series model is linear and the model creation fails when the system is strongly nonlinear. It is also limited to the response function being appropriate for the simulated groundwater system. Metran uses a gradient search method in the parameter space, so it can be sensitive to initial parameter values in finding an optimal solution.

The model calculates an evaporation factor, f , that gives the importance of evapotranspiration compared to precipitation. It is possible to use this factor to calculate the recharge values as shown by Equation D2 in appendix D. However, it must be noted that the use of Equation D2 is based on too many assumptions that are easily violated. Because of this, the equations should be applied only to long-term averages using only models of the highest quality.

Following the definitions used in the TACTIC project (Karlsson et al., 2020), this recharge quantity corresponds to the effective precipitation. It is equal to the potential recharge when the surface runoff is negligible. This in turn is equal to the actual recharge at the groundwater table if there is also no storage change or interflow.

4.1.4 Irish Groundwater Recharge Method

The Irish Groundwater Recharge Map is a spatially-distributed lumped hydrogeological model of average annual recharge to the deep groundwater system. The 'deep groundwater' is conceptualised as the resource that can be tapped steadily year-round and where yields aren't significantly influenced by seasonal changes in water table or extended dry periods. In addition to the 'deep groundwater' recharge, 'potential recharge' is also estimated. Conceptually, this is the water that percolates into the subsurface below the rooting zone, but may move sideways as interflow, or may have a relatively short residence time in the aquifer and not become part of the sustainable groundwater resource.

The recharge amount is shown in units of millimetres per year (mm/yr). It was calculated on a daily time-step over the period 1981–2010 and then averaged to give a yearly amount.

For WP4, the map is derived from two elements:

- (1) existing and new hydrogeological data layers that are combined to give recharge coefficients, and;
- (2) new agri-meteorological data layers.

Geological and hydrogeological map inputs include: soil drainage, subsoil permeability, groundwater vulnerability, peat, sand/gravel aquifer, and bedrock aquifer class.

The geological and hydrogeological maps are combined to generate 24 groundwater recharge coefficients using a ‘geological engine’ outlined in Hunter Williams et al. (2013). These are summarised in Hunter Williams et al. (in press) and in the Table in **Appendix E**. They are a slight update from Hunter Williams et al. (2013). The key improvements are summarised in a table in **Appendix E**.

The recharge coefficient polygons multiply agri-meteorological input data (Effective Rainfall, ER), as shown in the flow diagram in **Appendix E**. The ERI is on a 2.5 x 2.5 km grid and was produced by Irish Centre for High-End Computing (ICHEC) from downscaled numerical weather prediction (NWP) models (MÉRA, produced by Met Éireann). The FAO Penman Monteith Method was applied to dataset variables to produce reference evapotranspiration (ET_0), and the Soil Moisture Deficit Model (Schulte et al. 2005) was used to produce ET_a , SMD and ER variables used for this study.

4.1.5 Climate data

The TACTIC standard scenarios are developed based on the ISIMIP (Inter Sectoral Impact Model Intercomparison Project, see www.isimip.org) datasets. The resolution of the data is 0.5°x0.5° global grid and at daily time steps. As part of ISIMIP, much effort has been made to standardise the climate data (e.g. bias correction). Data selection and preparation included the following steps:

1. Fifteen combinations of RCPs and GCMs from the ISIMIP data set were selected. RCPs are the Representative Concentration Pathways determining the development in greenhouse gas concentrations, while GCMs are the Global Circulation Models used to simulate the future climate at the global scale. Three RCPs (RCP4.5, RCP6.0, RCP8.5) were combined with five GCMs (noresm1-m, miroc-esm-chem, ipsl-cm5a-lr, hadgem2-es, gfdl-esm2m).
2. A reference period was selected between 1981–2010 and an annual mean temperature was calculated for the reference period.
3. For each combination of RCP-GCM, 30-years moving average of the annual mean temperature were calculated and two time slices identified in which the global annual mean temperature had increased by +1 and +3 degree compared to the reference period, respectively. Hence, the selection of the future periods was made to honour a specific temperature increase instead of using a fixed time-slice. This means



- that the temperature changes are the same for all scenarios, while the period in which this occur varies between the scenarios.
4. To represent conditions of low/high precipitation, the RCP-GCM combinations with the second lowest and second highest precipitation were selected among the 15 combinations for the +1 and +3 degree scenario. This selection was made on a pilot-by-pilot basis to accommodate that the different scenarios have different impact on the various parts of Europe. The scenarios showing the lowest/highest precipitation were avoided, as these end-members often reflects outliers.
 5. Delta change values were calculated on a monthly basis for the four selected scenarios, based on the climate data from the reference period and the selected future period. The delta change values express the changes between the current and future climates, either as a relative factor (precipitation and evapotranspiration) or by an additive factor (temperature).
 6. Delta change factors were applied to local climate data by which the local particularities are reflected also for future conditions.

For the analysis in the present pilot the following RCP-GCM combinations were employed (**Table 2**):

Table 2: Combinations of RCPs-GCMs used to assess future climate

		RCP	GCM
1-degree	"Dry"	rcp6p0	hadgem2-es
	"Wet"	rcp4p5	gfdl-esm2m
3-degree	"Dry"	rcp4p5	hadgem2-es
	"Wet"	rcp4p5	miroc-esm-chem

Table 3: Yearly average delta change factors per climate change scenario for the Ireland Midlands & SE Region pilot area

	1C Min	1C Max	3C Min	3C Max
Precipitation	0.990	1.035	0.973	1.078
PET	1.006	1.053	1.060	1.062

The yearly average delta change factors shown in **Table 3** above do not show any major variation in nether PET nor precipitation rates. In contrast, the monthly delta change (non-averaged) factors shown in **Figure 8** below highlight a greater range of values, more so in PET variation across the midlands & SE region of Ireland.

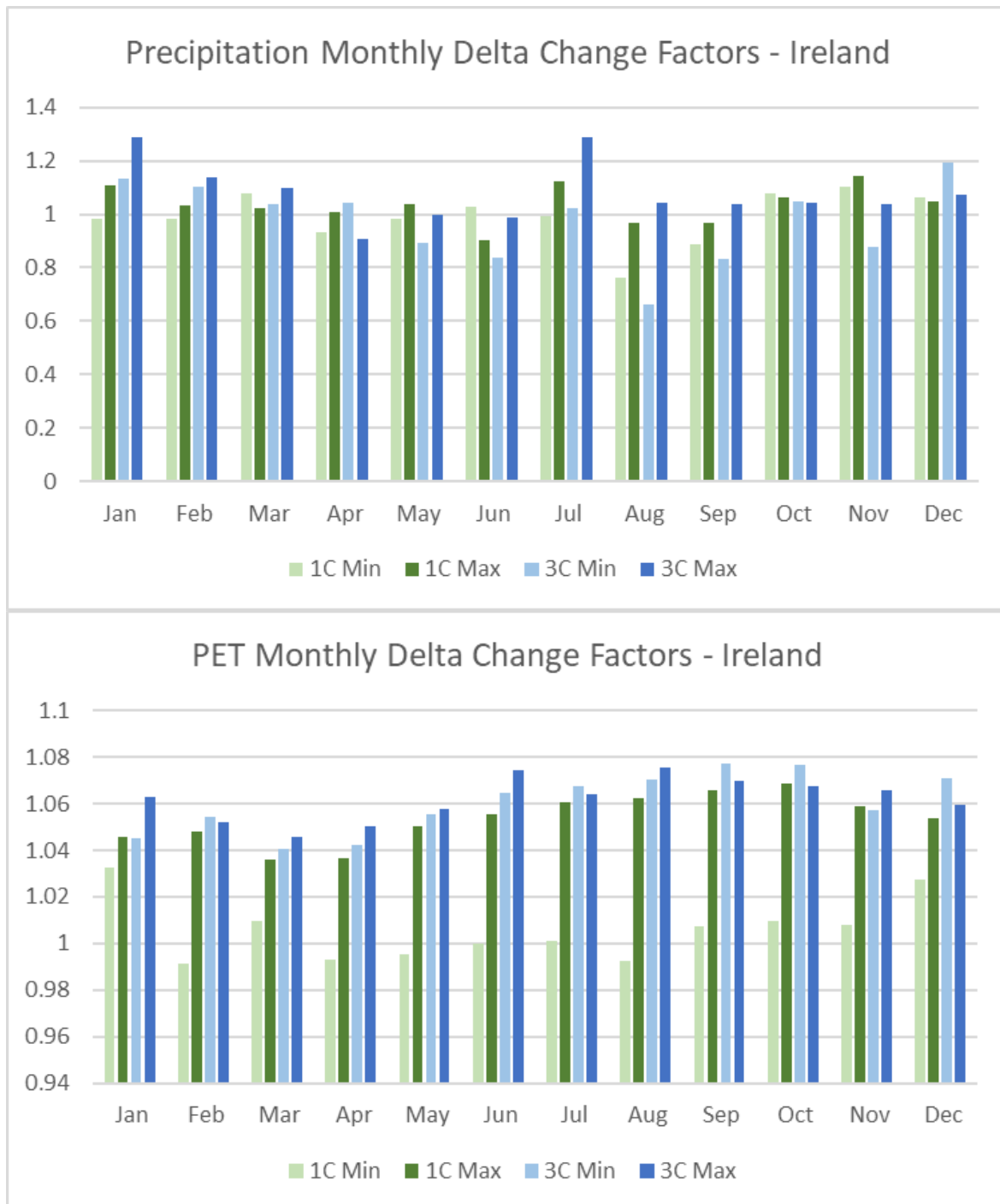


Figure 8. Comparison of monthly precipitation and PET delta change factors for the Ireland Midlands & SE region pilot area



4.1.6 Tool(s) / Model set-up

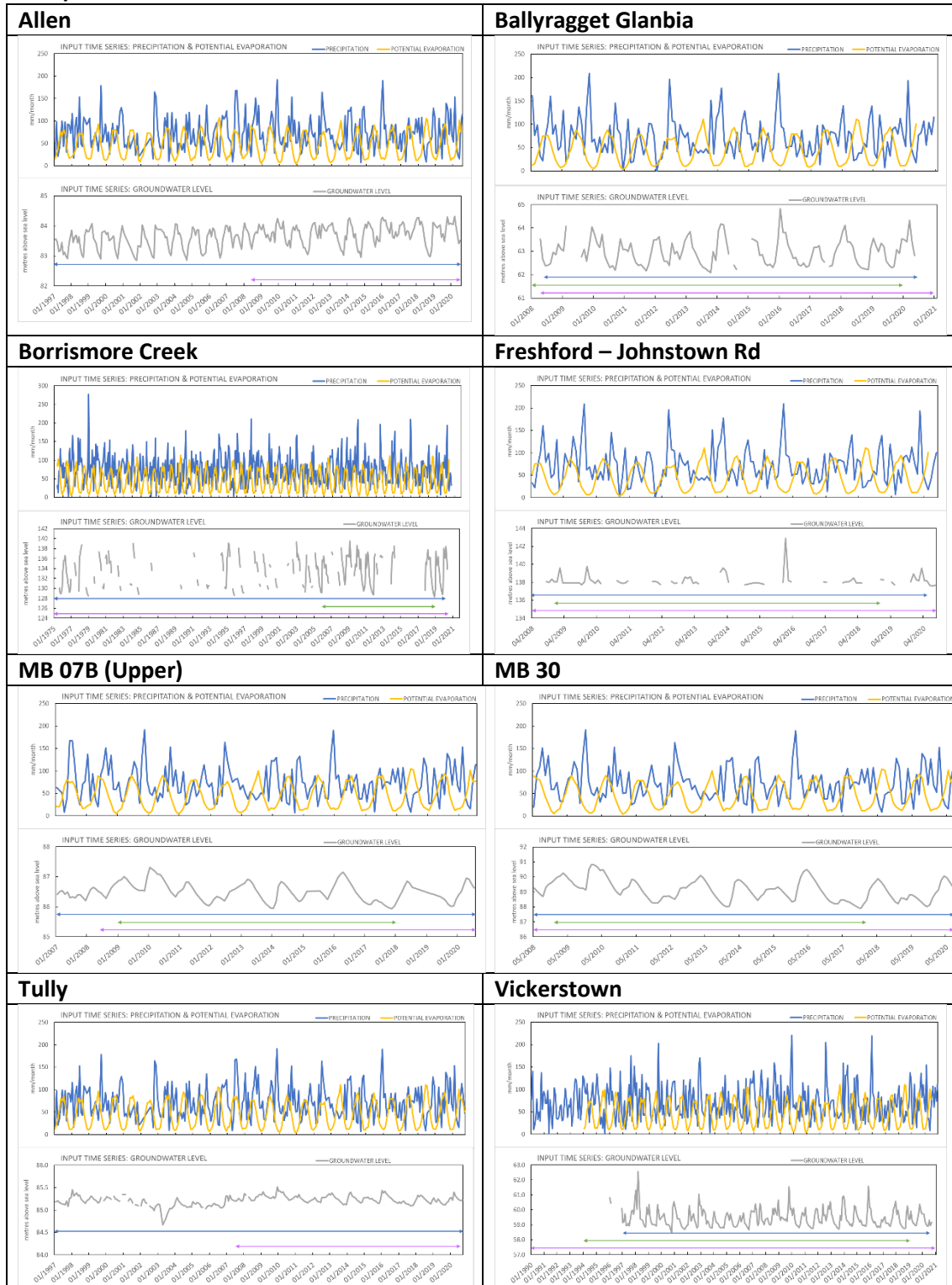
AquiMod

AquiMod model setup relies primarily on two input files. The first, “Input.txt”, is a control file where the module types and model structures are defined. AquiMod is executed first under a calibration mode where a range of parameter values of the different selected modules are given in corresponding text files, and a Monte Carlo approach is used to select the parameter values that yield the best model performance. “Input.txt” also controls the mode under which AquiMod is executed, the number of Monte Carlo runs to perform, the number of models to keep with an acceptable performance, and the number of runs to execute in an evaluation mode.

The second file AquiMod uses is called “Observations.txt”. This file contains the groundwater level observations and the forcing data, mainly the potential evapotranspiration (PET) and rainfall. However, it is also possible to include the anthropogenic impact on groundwater levels by including a time series of abstraction data in this file. None of the boreholes in this study include abstraction data, as part of the selection criteria for a borehole was to have no known influences from abstraction. The data are provided to the model on a monthly basis, and this forces AquiMod to run using a time step length of one month. However, PET and rainfall values are recorded in “Observations.txt” in mm/day which were calculated by dividing the monthly sum of PET and rainfall by the average number of days per month. **Table 4** shows observed monthly time series data of rainfall and PET as well as water level fluctuations at the different boreholes.

All AquiMod models built for the boreholes in **Table 1** use the FAO Drainage and Irrigation Paper 56 (Allen et al./ FAO, 1988) method in the soil module, and employ the two-parameter Weibull probability density function to control the movement of infiltrated water in the unsaturated zone (**Appendix C**). For the groundwater module structure, the simplest structure with one layer and one discharge feature, was selected. Due to limited resources, it was not possible to test more complex structures on each of the boreholes. The model that yielded the best NSE score was selected to undertake the recharge calculations.

Table 4: Rainfall, Potential Evapotranspiration and Groundwater level time series and modelling periods for each model type. Blue arrow = AquiMod; green arrow = GARDENIA; and pink arrow = Metran



GARDENIA

The GARDENIA model represents the water cycle in a basin from rainfall received by the soil surface until the river flow at the outlet, and/or the aquifer level at a given point. GARDÉNIA is a lumped model because it considers a lumped input (rainfall and potential evaporation representative for the basin) averaged over a catchment area and a single output (river flow at the outlet and/or groundwater level in the aquifer).

A lumped hydrological model simulates, through a series of reservoirs, the main mechanisms of the water cycle in a catchment (rainfall, evapotranspiration, infiltration, and runoff). Indeed, the exponential form of the recession of river flows or aquifer levels looks like the emptying of a reservoir (or tank). Therefore, the behaviour of an aquifer system can be represented by a series of inter-connected tanks. Non-linear transfer functions improve the capability of this schematic representation to simulate a complex system.

GARDENIA simulates the water cycle through a series of 3 or 4 connected tanks that represent respectively (**Figure 9**):

- the few decimetres of the soil that are subjected to the influence of evapotranspiration (root zone of the present vegetation).
- an intermediate zone generating rapid flow.
- one or two aquifer zones generating delayed slow flow.

The outflow from one reservoir to another is controlled by simple laws, specific to each reservoir; these laws are governed by the model parameters (active storage, duration of outflow, overflow threshold, etc.).

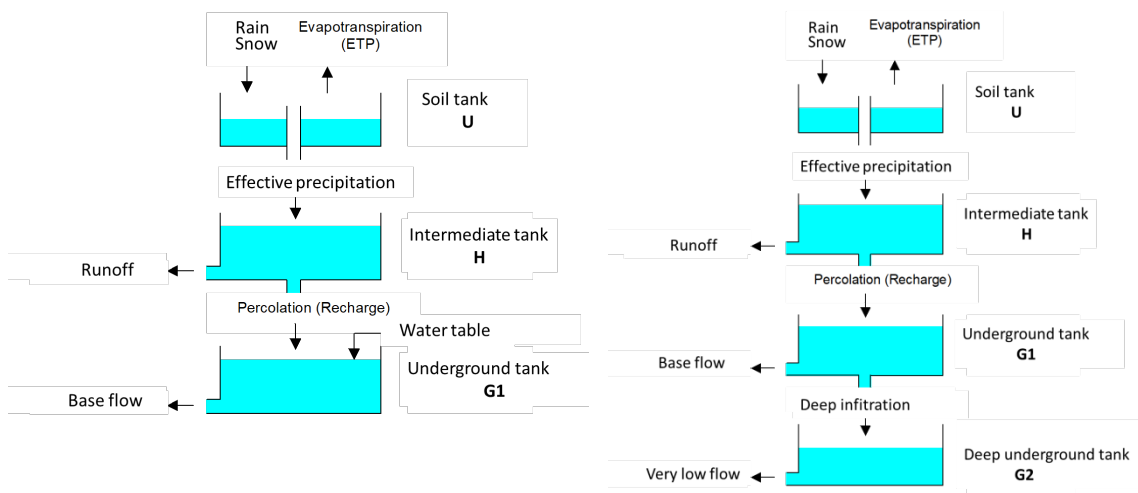


Figure 9 : Schematic representation of GARDÉNIA with one underground reservoir (left) or two underground reservoirs (right)

Production function and transfer function

The calculation consists of two parts, traditionally called: "production" function and "transfer" function.

The "production" function determines the amount of water reaching the system, and the amount that will evaporate or that will infiltrate into the lower horizons to emerge "later". The "transfer" function determines at what time the water, which has not evaporated, leaves the outlet of the basin or will reach the aquifer below. The transfer is represented as the passing of water through the 2 or 3 lower reservoirs of the model.

Due to the lumped nature of the model and the complexity of the hydrological system in reality, the different parameters of the tanks cannot be determined *a priori* from the local physiographical characteristics of the catchment (geology, vegetation cover, etc.).

Model data and parameters

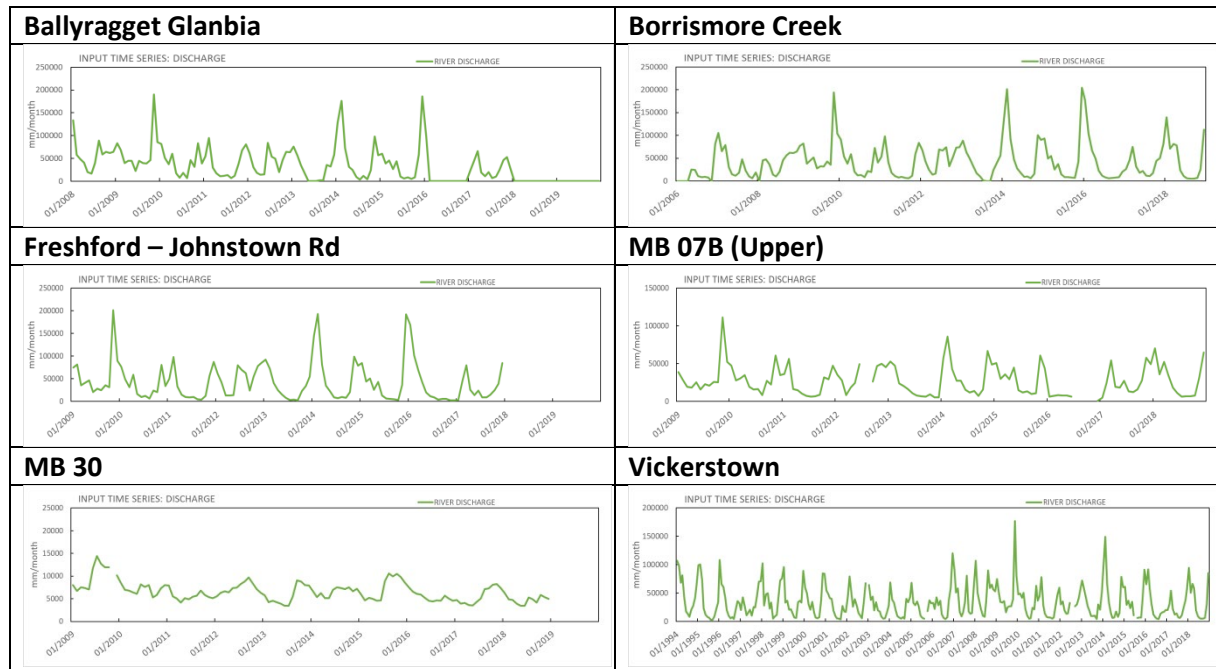
The required data are:

- a continuous time series of rainfall data.
- a continuous time series of potential evapotranspiration data (PET). PET values can be either calculated from sunshine duration, air temperature and relative humidity data, or can be obtained directly at Meteorological offices.
- one or two series of observations, which may include gaps, of:
 - river flows at the basin outlet (table x below observed discharge data used in GARDENIA); and / or representative groundwater levels at an observation well located in the basin.
- possibly a series of water withdrawals (pumping).

These different series of data must at a regular time step: daily, 5 days, 10 days, or monthly. It is also possible to use any regular time step (5 minutes, 1 hour, 60 days etc.). All the series should refer to the same period. The time step of each series is not necessarily identical (e.g. daily rainfall and monthly PET).

Input groundwater level and meteorological data are shown in **Table 4**, and river flow data are shown in **Table 5**.

Table 5: Input time series of river flow (discharge) associated with the borehole groundwater levels modelled in GARDENIA



Hydro(geo)logical parameters

In general, a number of 4 to 6 parameters (maximum 8 parameters) is required by the model (15 parameters in case precipitation in form of snowfall are to be taken into account). The dimensional parameters characteristics of the different reservoirs are (**Figure 10**):

- RUMAX (mm): capacity of reservoir RU, or the storage available for evapotranspiration.
- THG (months): time of half-filling of reservoir G.
- RUIPER (mm): level in reservoir H for which there is an equal distribution between fast runoff and percolation.
- TG1 (months): time of half-recession of reservoir G1.
- TG12 (*) (months): time of half-filling or reservoir G2 (time of half-transfer from G1 to G2).
- TG2 (months): time of half-recession of reservoir G2 (time of half- slow recession).

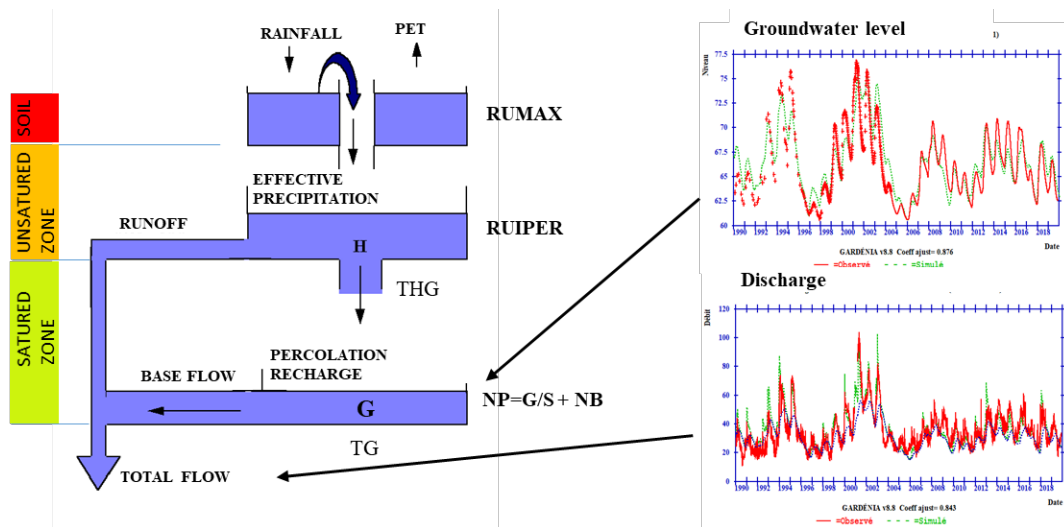


Figure 10 : Principle of GARDÉNIA global hydrological model for simulating the flow of a watercourse and/or a groundwater level.

Metran

Metran applies transfer function noise modelling with daily precipitation and evaporation as input and of groundwater levels as output (Zaadnoordijk *et al.*, 2019). The setup is shown in **Figure 11**. If time series of other influences on the groundwater head are available, these contributions can be added to the deterministic part of the model. An input file that holds the daily information of precipitation, potential evaporation and groundwater levels is prepared for each borehole in **Table 1**. Plots of these data are shown in **Table 4** above. It must be noted that, while Freshford–Johnstown Rd and Borrismore Creek groundwater levels used in Aquimod and GARDÉNIA and shown in **Table 4** have missing values, these have to be provided as complete time series to Metran. To achieve this, a linear interpolation procedure is used to fill in the missing values in the groundwater level time series. Once executed, it calculates the characteristics of the impulse functions and the corresponding parameters automatically.

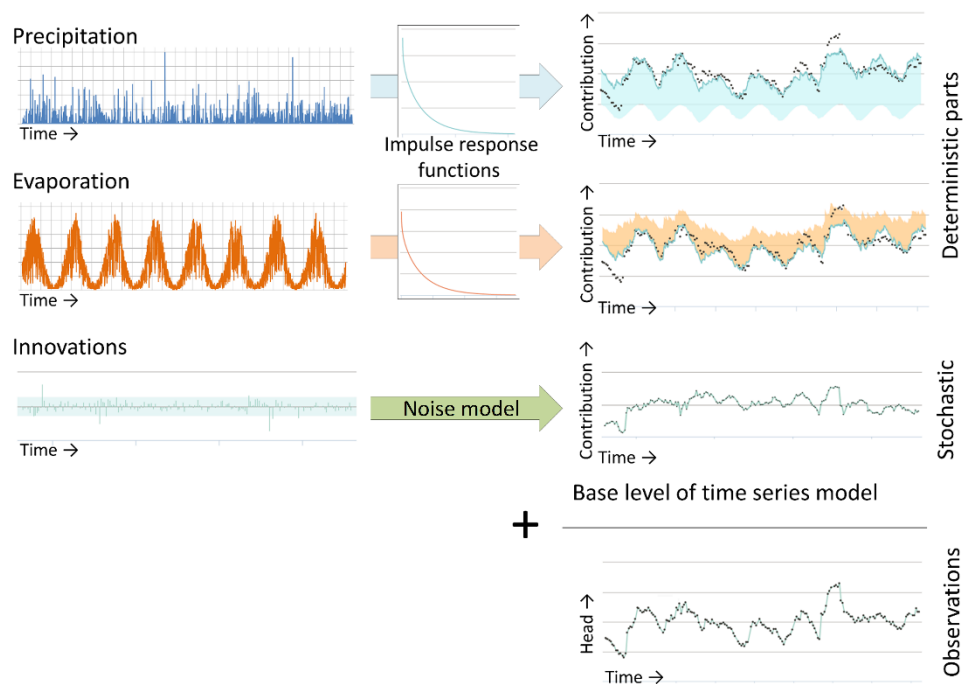


Figure 11 : Principle of Metran for simulating the groundwater level over time at a location.

Irish Groundwater Recharge method

The output from the Irish Groundwater Recharge method is a spatially-distributed estimate of average annual groundwater recharge. The method uses a lumped approach to model:

- (1) 'potential recharge' – this is the water that percolates into the subsurface below the rooting zone, but may move sideways as interflow, or may have a relatively short residence time in the aquifer and not become part of the sustainable groundwater resource;
- (2) 'deep groundwater' resource – this is conceptualised as the resource that can be tapped steadily year-round and where yields aren't significantly influenced by seasonal changes in water table or extended dry periods

Model inputs are:

- 1) The geological and hydrogeological data layers that represent the controls on infiltration and percolation, and on recharge acceptance: soil drainage and modified soil drainage; subsoil permeability; groundwater vulnerability and (indirectly) subsoil thickness; subsoil type (for peat, sand and gravel); aquifer type and class (for sand/gravel aquifers and the poorest three bedrock aquifer classes);
- 2) The meteorological and agronomic data layers that produce the effective rainfall.

The geological and hydrogeological maps are combined to generate 24 groundwater hydrogeological scenarios and associated recharge coefficients as outlined in **Table E.2, Appendix E**. The hydrogeological scenarios and recharge coefficients are a slight update from



Hunter Williams et al. (2013) (see **Table E.1** for summary of improvements). The hydrogeological scenarios give a minimum, maximum and inner range of expected recharge coefficient. For the national map, the mid-point of the inner recharge coefficient range is used. (For site-specific studies, other recharge coefficient values within the outer range can be chosen.)

To derive an estimate of potential or long-term (deep) recharge, the recharge coefficient polygons multiply agri-meteorological input data (Effective Rainfall, ER), as shown in the flow diagram in **Figure 12**. This gives the Potential recharge value. If the bedrock aquifer is poorly productive (in Ireland: LI, PI and Pu aquifer categories), a maximum recharge capacity is applied to simulate the limited recharge acceptance of poorly fractured, low storage aquifers.

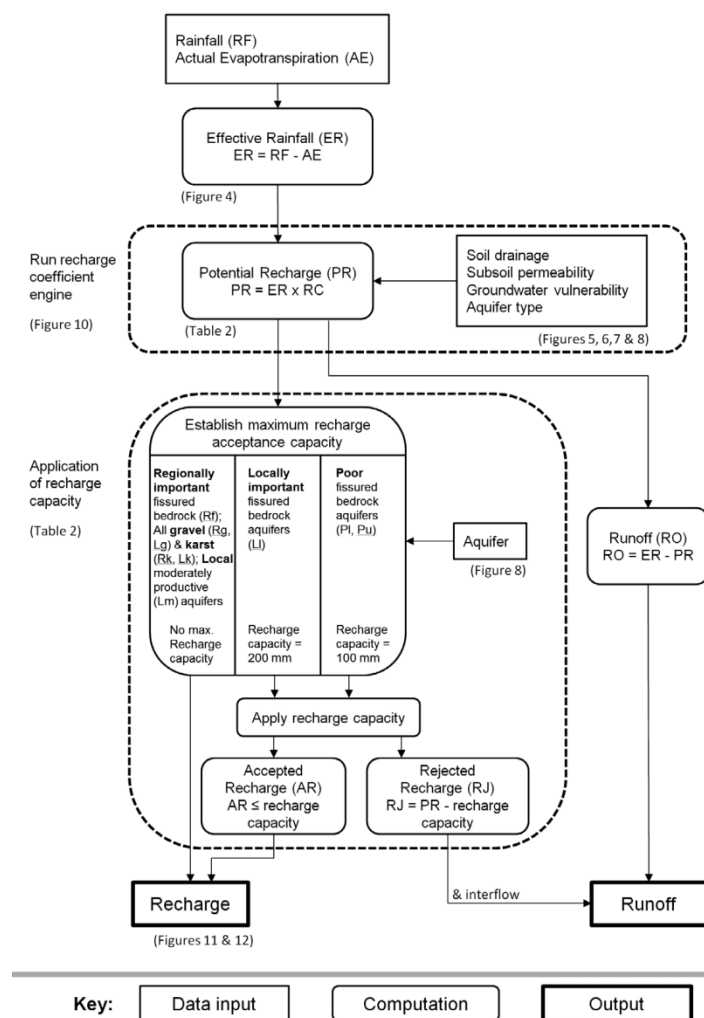


Figure 12. Indicative structure and method of GIS-based tool for estimating recharge (from Hunter Williams et al., 2013). RF, total rainfall; AE, actual evapotranspiration; ER, effective rainfall; PR, potential recharge; RC, recharge coefficient; RO, runoff.

The input ER is on a 2.5 x 2.5 km grid and was produced by Irish Centre for High-End Computing (ICHEC; Werner et al., 2019) from downscaled numerical weather prediction (NWP) models. To derive the ER, three climate models were evaluated, and MÉRA, produced by Met Éireann, was chosen as it had the highest overall skill. The FAO Penman Monteith Method was applied to dataset variables to produce reference evapotranspiration (ET_0), and the Soil Moisture Deficit Model (Schulte et al. 2005) was used to produce ET_a , SMD and ER variables used for this study.

The groundwater recharge amount is presented in units of millimetres per year (mm/yr). It was calculated on a daily time-step over the period 1981-2010 and then averaged to give a yearly amount. It is therefore temporally one-dimensional, but spatially two-dimensional. Annual recharge

4.2 Initialization

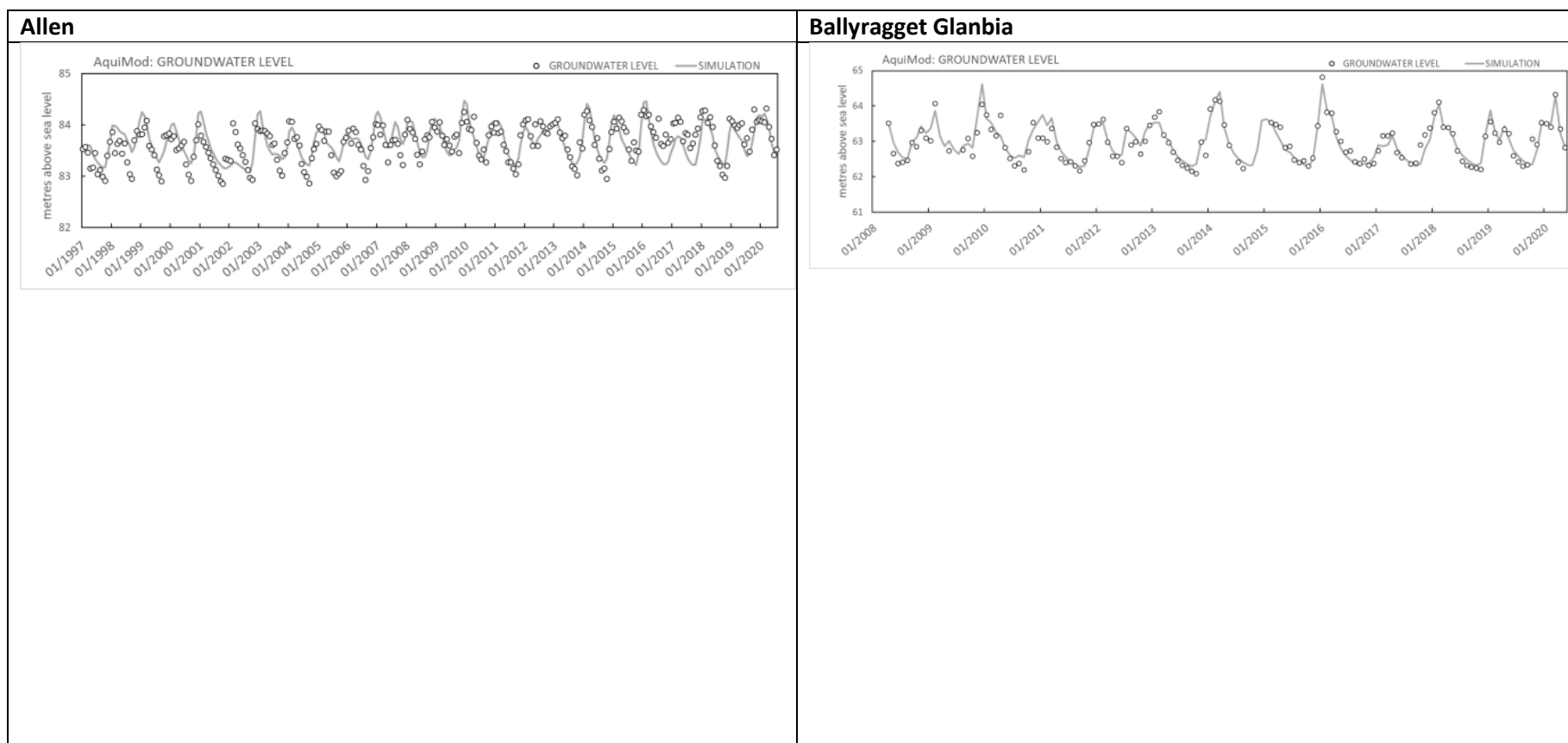
It is evident that due to the sometimes considerable hydrological inertia of the system, the calculation of the first values depends a lot on the conditions of the previous years. To avoid the difficulties that could result from the above, the possibility has been introduced in the Aquimod, GARDENIA and Metran models to take into consideration a few years, prior to the first hydrological observations. However, since it often takes very long for the flow regime to establish, the model is placed in hydrological equilibrium at the beginning of calculations, this means that the outcoming flow (or piezometric level) corresponds to incoming effective rainfall.

4.3 Tool(s)/ Model calibration/ test

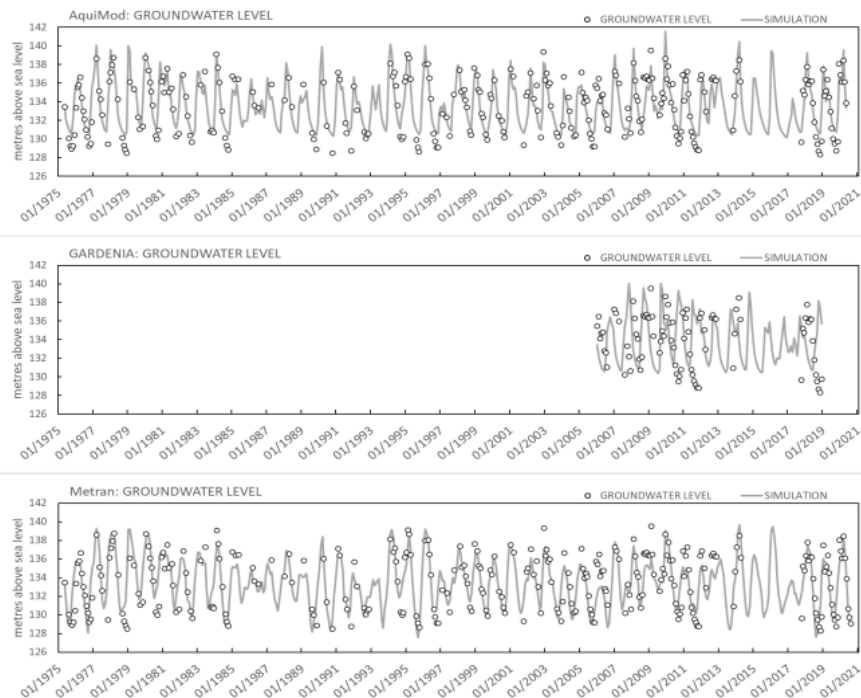
4.3.1 Observation data

Graphs of groundwater levels at all monitoring stations are shown in **Table 4**, river flows associated with groundwater monitoring stations are shown graphically in **Table 5**. Observed vs simulated groundwater levels and river flows (for Gardenia models) are shown in **Table 6**. Data for models which failed calibration tests have not been included.

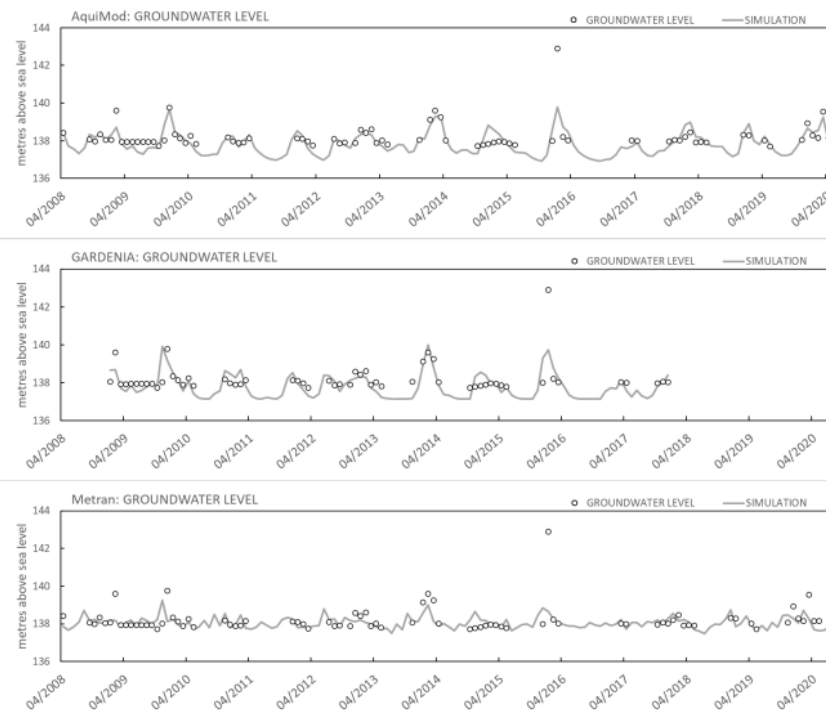
Table 6: Observed vs. simulated groundwater levels for each model type and reference period. Modelling periods vary due to the data requirements of each model. For example, both Metran and GARDENIA can operate without groundwater level data at the start of the modelling period. However, Aqumod must start with an observed groundwater level. Models which failed calibration tests have not been included.



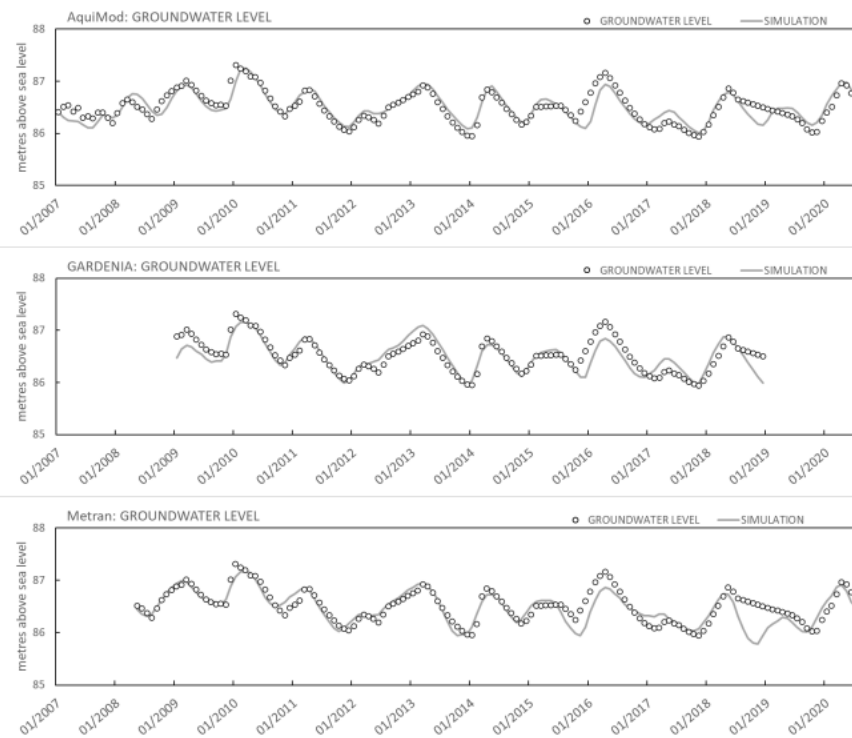
Borrismore Creek



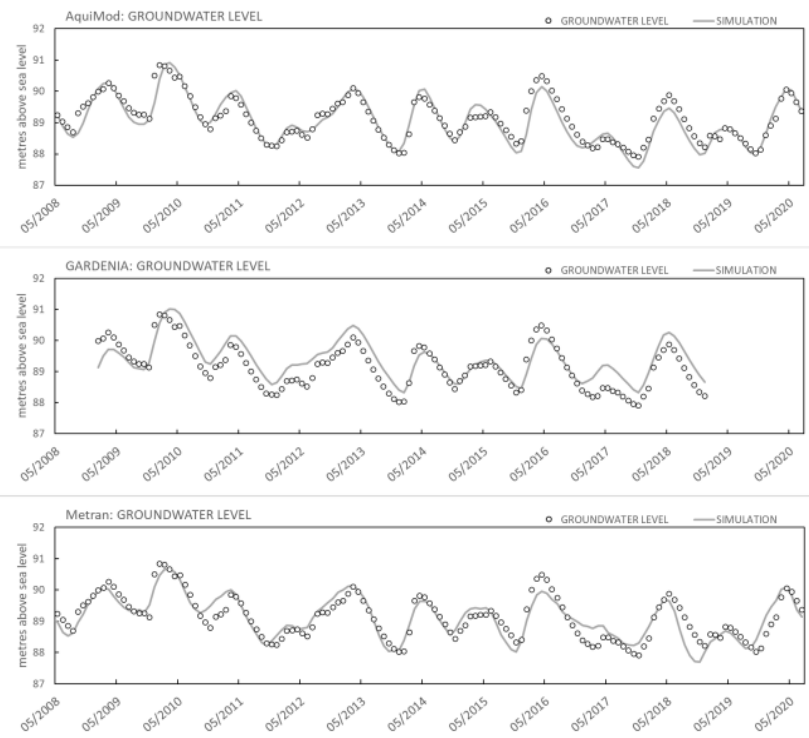
Freshford – Johnstown Rd



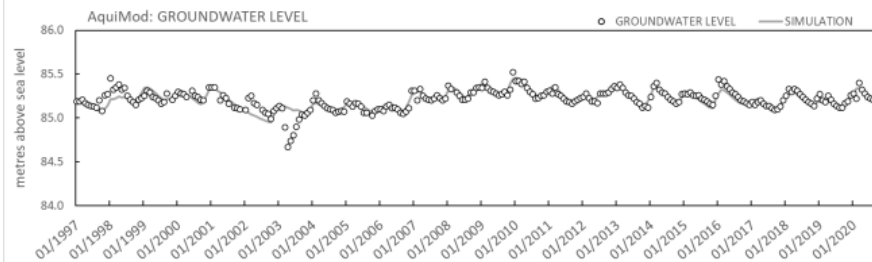
MB 07B (Upper)



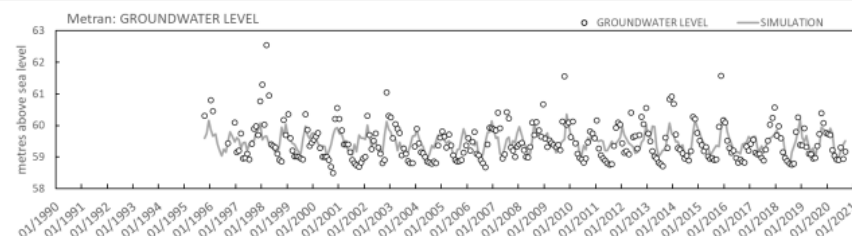
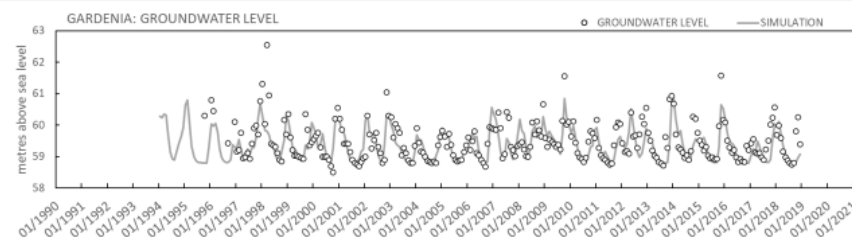
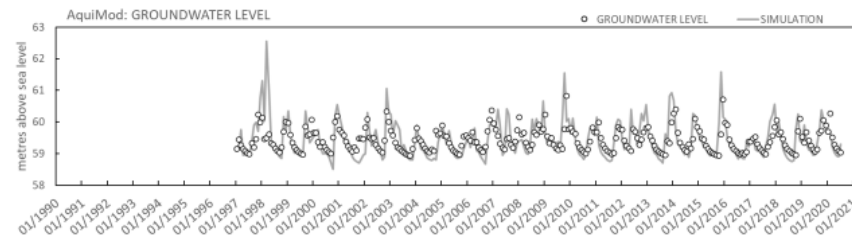
MB 30



Tully



Vickerstown



4.3.2 Calibration of *AquiMod* models

The calibration of *AquiMod* is performed automatically using the Monte Carlo approach. The user populates the files of the selected modules with minimum and maximum parameter values and then the model randomly selects a value from the specified range for any given run. The selection of the minimum and maximum values is physically based depending on the characteristics of the study area. For example, the minimum and maximum values of the storage coefficient in the saturated zone module are set to lower values in a fractured karst limestone aquifer compared to those used for a gravel aquifer.

A conceptual understanding of the hydrogeological system must be available before the use of *AquiMod*, since this is necessary to set the limits of the parameter values for the calibration process. In some cases, it is not possible to obtain a good performing model with the selected values and that necessitates the relaxation of these parameters beyond the limits informed by the conceptual understanding. In such cases, the parameter values must feed back into the conceptual understanding if better performing models are obtained.

AquiMod execution time is relatively small, which allows the calibration of the model using hundreds of thousands of runs in couple of minutes. The performance measure used to assess the quality of the simulation is the Nash Sutcliffe efficiency (**Appendix C**) that takes a maximum value of unity for a perfect match between the simulated and observed data. The threshold at which models are accepted is set to a value of 0.1. All the models that achieve an NSE higher than 0.1 are included in the analysis but a maximum number of 100000 runs are used if the number of acceptable models is greater than 100,000.

Table 7 shows the best NSE values obtained for the models calibrated at the boreholes listed in **Table 1**. It is clear that a good match was achieved between the simulated and observed groundwater levels as illustrated in the plots shown **Table 6**. The best performing model is produced from MB 30 data with an NSE value of 0.86 and is closely followed by Ballyragget Glanbia with an NSE of 0.85. The worst performing *AquiMod* model is produced with the Vickerstown borehole with an NSE value of 0.36.

4.3.3 Calibration of *GARDENIA* models

Model calibration in *GARDENIA* consists of adjusting model parameters, within given limits, with the aim of producing simulated river flows and/or groundwater level series that match the observed ones as precisely as possible.

The data required for calibration are:

- model "input" continuous series: rainfall and evapotranspiration (and air temperature if snowmelt is taken into consideration);
- model "output" observed series (flows or levels) not necessarily continuous, but covering a concomitant period with the input series.

Calibration is done in a semi-automatic way. The user provides an initial set of parameters and indicates which parameters should be optimised. The model uses a non-linear optimisation algorithm adopted from the Rosenbrock method. The model makes the chosen parameters



vary (within a range of values defined by the user) and searches for a set which gives the best fit between observed and simulated series has been found.

The model produces the following results:

- For each time-step a water balance of the different components of the hydrological cycle (runoff, actual evaporation, groundwater flow, etc.).
- A graphical representation of observed and simulated values for a visual evaluation of the calibration.
- Numerical criteria for the evaluation of the quality of calibration.

Taking into account this information, the user then estimates whether to attempt a new optimization from another set of parameters. When both the numerical fitting criteria and the graphs for visual comparison are satisfactory, the user may consider which set of parameters are representative of the catchment as far as the obtained values are realistic. The user may then test different values of the parameters around this solution, in order to determine the family of parameter values that are representative, i.e., acceptable from point of view, of the water cycle (sensitivity study).

Table 7 summarises the best model efficiency scores for the models calibrated by GARDENIA for the boreholes listed in **Table 1** and shown in **Table 6**. The majority of models achieved a good match between the simulated and observed groundwater levels, with five out of six boreholes producing positive groundwater level NSE values, ranging from 0.33 (Vickerstown) to 0.80 (MB 07B). Four of these five models also achieved good river flow NSE values, with the exception of MB 30 which produced a river flow NSE of -102.55. We acknowledge that this is not an ideal NSE score. However, given that the quality of AquiMod models are based on its groundwater level NSE score, we deemed this a passable result. Ballyragget Glanbia did not pass model efficiency tests, scoring negative NSE values for both the groundwater level (-0.24) and river flow (-0.26) time series. Therefore, this borehole has not been used for climate projections.

Limitations and specific difficulties in the simulation of piezometric levels

The GARDENIA model has been developed to simulate river flows as well as piezometric levels indifferently: in fact, the hydrological scheme is the same; the level in the underground reservoir can be thought of as being linked to the piezometric level by a linear relationship irrespective of the type of the aquifer considered.

The storage coefficient then plays the role of an amplitude factor, like the surface area of the catchment in the case of the calculation of flows. Nevertheless, the simulations of levels involve very specific problems.

The storage coefficient is not known, not even in order of magnitude, whereas the surface area of catchment is generally known. In fact, it represents a coefficient of global influence of the fluctuations of a reserve on a particular piezometric level. This coefficient of influence will only be equal to the average storage coefficient of the aquifer if the point of observation is located far away from any watercourse. This coefficient cannot be linked easily to interpretations of pumping tests (whose validity remains local) and which are often carried out



over short periods and can give a confined aquifer storage coefficient. The storage coefficient in GARDENIA corresponds more to level variations over periods that are much longer and the type of storage coefficient to be taken into consideration is that of an unconfined aquifer. Moreover, the storage coefficient in its traditional meaning is most frequently defined only with a precision far below 20 %, while deviation of 20 percent in the balance equation is difficult to accept.

In case of simulations of groundwater levels only (and not conditioned to river flows), the water balance established should be interpreted as an analysis of the flux only with extreme care. Although this method of analysis may be a bit dangerous for effective input estimations, it is often the only method available, and it should thus not be rejected in advance.

4.3.4 Calibration of Metran models

For the standard setup with precipitation and evaporation, there are five parameters that have to be determined during the calibration of the model. Three parameters are related to the precipitation response, the evaporation factor, and the noise model parameter (**Appendix D**). There are three extra parameters for each additional input series, such as pumping. The parameter optimization of Metran uses a gradient search method in the parameter space to reach a global minimum. As explained in **Appendix D**, two parameters indicate if Metran succeeded in producing a match between the simulated and observed data. These are called the *Regimeok* and *Modok*. When *Regimeok* is equal to one, the calibration is of highest quality. If *Modok* is equal to one and *Regimeok* is equal to zero, the calibration is of acceptable quality. Finally, if both parameters are equal to zero, the calibration quality is insufficient.

Table 7 shows the performance of Metran across the Irish boreholes considered in this study. It is clear that according to criteria set above, Metran fails to produce a model at three boreholes but succeeds at the five other boreholes with the model output showing highest quality at four of these boreholes (with highest value of R^2). Models which failed the calibration tests have been excluded from historical and future recharge calculations.

Table 7: Modelling periods used per model type and performance parameter scores. AquiMod and GARDENIA assess the groundwater level model efficiency using Nash Sutcliffe Efficiency (NSE) and Metran summarizes the quality using two binary parameters, Regimeok and Modok, with more detailed model quality information given with R2 and RMSE.

Monitoring point name	Models used	Observation period	NSE (GWL)	NSE (river flow)	regimeok	modok	Overall quality	R2	RMSE
Allen	AquiMod	01/1997 – 07/2020	0.54						
	Metran	05/2008 – 07/2020			0	0	Insufficient	0.14	0.3
Ballyragget Glanbia	AquiMod	04/2008 – 05/2020	0.85						
	GARDENIA	01/2008 – 12/2019	-0.24	-0.26					
	Metran	03/2008 – 12/2020			0	0	Insufficient	-0.7	0.69
Borrismore Creek	AquiMod	05/1975 – 05/2020	0.78						
	GARDENIA	01/2006 – 12/2018	0.65	0.83					
	Metran	05/1975 – 08/2020			1	1	Highest	0.75	1.49
Freshford – Johnstown Rd	AquiMod	04/2008 – 05/2020	0.48						
	GARDENIA	01-2009 – 12/2019	0.69	0.8					
	Metran	04/2008 – 08/2020			1	1	Highest	0.48	0.51
MB 07B (Upper)	AquiMod	01/2007 – 07/2020	0.77						
	GARDENIA	01/2009 – 12/2018	0.8	0.14					
	Metran	05/2008 – 07/2020			1	1	Highest	0.87	0.12
MB 30	AquiMod	05/2008 – 07/2020	0.86						
	GARDENIA	01/2009 – 12/2018	0.58	-102.55					
	Metran	04/2008 – 07/2020			1	1	Highest	0.81	0.3
Tully	AquiMod	01/1997 – 09/2020	0.64						
	Metran	06/2008 – 07/2020			0	0	Insufficient	0.56	0.05
Vickerstown	AquiMod	01/1997 – 07/2020	0.36						
	GARDENIA	01/1994 – 12/2018	0.33	0.35					
	Metran	01/1990 – 31/2020			0	1	Acceptable	0.42	0.44

4.3.5 Calibration of Irish Groundwater Recharge model

There is no structured calibration process for the Irish Groundwater Recharge Model. For the national map, the mid-point of the inner recharge coefficient range is used and is considered *a priori* to be appropriate. The map in **Figure 13** shows the long-term sustainable average annual groundwater recharge estimated using the Irish Groundwater Recharge method.

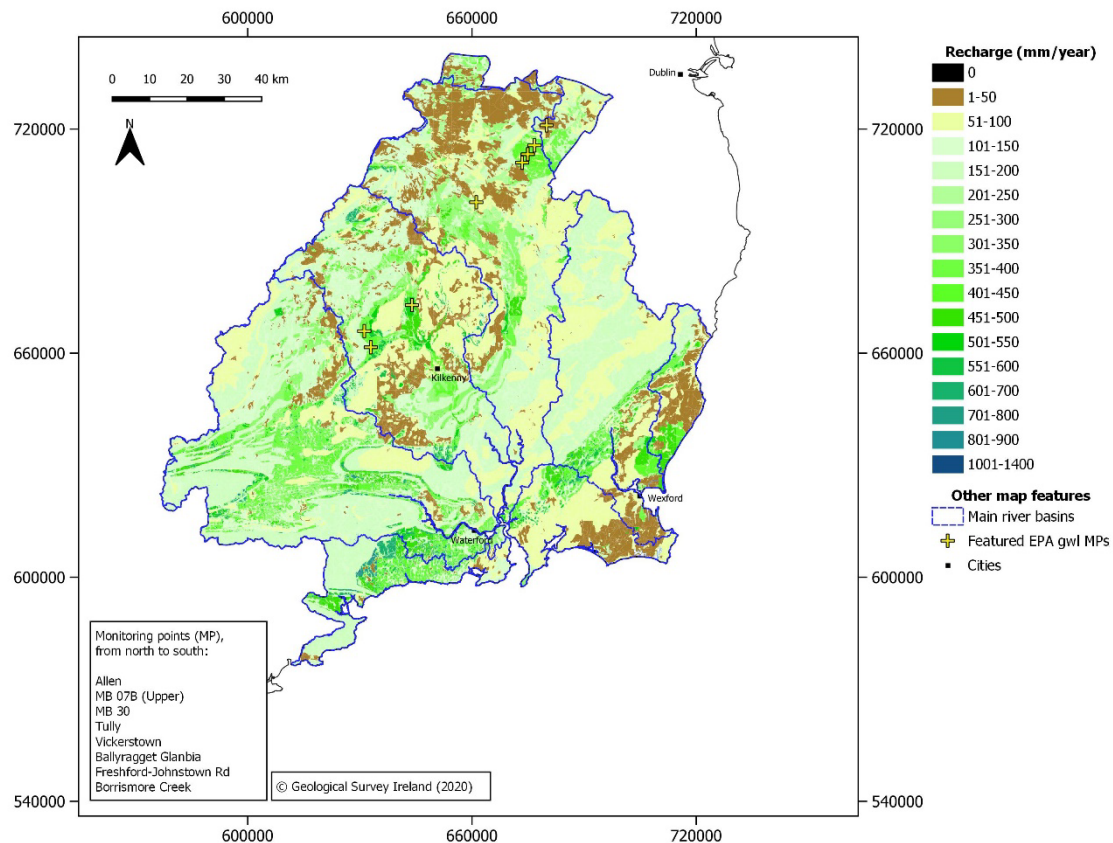


Figure 13. Long-term sustainable average annual groundwater recharge estimated using the Irish Groundwater Recharge method.

Whilst the recharge coefficients are assigned *a priori*, and groundwater recharge is forward modelled, the recharge coefficients summarised in **Table E.2 (Appendix E)** were based on a set of detailed studies summarised in Hunter Williams et al. (2013) and then extrapolated using expert judgement to cover the 24 scenarios.

Catchment-scale (10's – 100's km²) area-summed groundwater recharge from the national (average) map has been compared to catchment outflows and baseflow separations from gauging stations in two studies (Hunter Williams et al., 2011 and Mullarkey et al, 2021) and has been found to have good correspondence. For site-specific studies, other recharge coefficient



values within the outer range can be chosen on the basis of observed geological conditions, or to match observational data or recharge estimates derived from other methods.

4.4 Uncertainty

The selection of groundwater level monitoring points used in this study is based on research by Tedd *et al.* (2011). In the report, the authors analysed groundwater level data from a network of monitoring points in the southeast of Ireland and provide insights on the hydrogeological situation: grouping boreholes by catchment positioning; aquifer confinement; and influences on the groundwater levels such as abstraction, nearby rivers or discharge-dominated areas. These interpretations influenced our selection of monitoring points for the study, avoiding boreholes that were identified as being confined aquifers, abstraction- or river-influenced. However, it is possible the hydrogeological situation surrounding each borehole has changed since 2011.

The precipitation and potential evapotranspiration time series data were collected from rainfall and synoptic weather stations operated by Met Éireann. The Met Éireann database contains 353 rainfall stations in the pilot area, including historical records from weather stations which are no longer in use. **Figure 4** shows weather stations used in the study, and **Table 1** displays summary information relating to these stations. As precipitation data can vary over a relatively short distance, it was necessary to choose a station close to the borehole. However, the nearest stations did not always have data that ran the full length of the groundwater level monitoring period. Therefore, the next most appropriate station was selected. In some cases, the station used for rainfall can be up to approximately 17 km from the borehole (Tully). Potential evaporation data were also selected based on proximity and topographical suitability to the monitoring points, and came from three synoptic stations: Casement, Kilkenny, and Oakpark (**Table 1**). It is worth noting that the relatively short distance between some of the monitoring points meant the same rainfall and PET data are applicable for more than one borehole.

Suitable values for permeability and specific yield were assigned to the aquifers based on values derived from a bulk analysis of Irish aquifer types (Kelly *et al.*, 2015), as local pumping test and field data was not available for the boreholes at the time of this study. Therefore, these bulk values may not be accurate due to localised heterogeneity of aquifers resulting in hydrogeological properties.

Groundwater level data from Borrismore Creek and Freshford–Johnstown Rd (Freshford) are more inconsistent and, therefore, less reliable than the other boreholes in this study. The Borrismore Creek time series has a number of consecutive months of data missing; most notable is a large gap in recorded data from 2013 to 2017. The Freshford borehole is 13.5 m deep, and the bottom 1.2 m of the borehole consists of a sump. Consequently, the water level in the borehole does not drop below 12.3 m. During periods when the water level data is recorded as 12.3 m below ground level, this may not accurately reflect the actual groundwater level in the surrounding aquifer (Environmental Protection Agency, 2021) and, therefore, values below 12.3 m were removed from the time series before modelling. The missing

groundwater level data from both of these boreholes could impact the result of the model efficiency tests.

When comparing model results, it is worth emphasising the differences between each of the models' input parameters. For example, as well as using groundwater level, rainfall and potential evaporation data, GARDENIA also requires the input of: a catchment area, effective rainfall estimates for the catchment, and discharge data from an appropriate river flow station which acts as a proxy for the monitoring borehole. AquiMod requires a different suite of parameters for each module type which must be constrained during the calibration process (**Appendix C**). AquiMod also models the catchment size based on the linear distance to the nearest discharge zone, whereas GARDENIA requires a catchment area for the river flow station which is often much larger. Like AquiMod and GARDENIA, Metran also requires groundwater level and precipitation data, but uses an evaporation time series instead of a potential evaporation. Finally, both GARDENIA and Metran use daily timesteps for input observational data and also output time series on a daily timestep. AquiMod can run with daily timesteps. However, it produces much better model efficiency scores when monthly timesteps are used. The Irish Groundwater Recharge Model does not simulate groundwater levels; potential groundwater recharge is calculated at a daily timestep over the whole study area, but is summed and average over the reference period (1981-2010).

There are also variations between the modelling period for each model type. One of the benefits of Metran is that it can produce results with discontinuous groundwater level data and without any groundwater level data at the start of the modelling period. Therefore, if the groundwater level time series is relatively short and there are precipitation data which precedes it, you are able to execute Metran and produce results. Similarly, GARDENIA is able to function without groundwater level time series at the start of the modelling period, as long as a discharge time series are available. AquiMod, however, must have groundwater level data input for the start of the modelling period. Most of the boreholes modelled in Metran and AquiMod share similar modelling periods, with the exception of Allen, Tully, and Vickerstown. Generally, the time series lengths for each monitoring borehole in GARDENIA are shorter than in AquiMod and Metran. This is due to the fact that there must be direct coherence between the groundwater level data lengths and discharge data. With shorter river discharge data time series available, the groundwater level time series had to be clipped to the length of the discharge series.

5 RESULTS AND CONCLUSIONS

5.1 Historical recharge values

Long-term average (LTA) recharge estimated using the different models is shown in **Figure 14**.

- LTA recharge for AquiMod and GARDENIA was calculated using the recharge time series output by the best models.
- A recharge time series is not produced directly from Metran. Instead, LTA recharge is calculated using the formula $R = P - fE$ (**Appendix D**), where R recharge, P precipitation, f evaporation factor, and E evaporation. As mentioned in Appendix D, the formulas used to calculate recharge from Metran results are based on assumptions that can be easily violated. Therefore, the equations should only be applied to LTA rainfall and evaporation data and using only models of the highest quality.
- To derive an estimate of (a) Potential Recharge, the agri-meteorological input data (Effective Rainfall, ER) are multiplied by the recharge coefficient polygons (**Figure 12**). (b) long-term (deep) recharge is restricted if the bedrock aquifer is poorly productive (in Ireland: LI, PI and Pu aquifer categories), so a maximum recharge capacity is applied to simulate the limited recharge acceptance of poorly fractured, low storage aquifers.

Table 8 displays the historical recharge time series simulations from AquiMod and GARDENIA. Clear differences are observed between the mean and range of recharge values produced by the two models. Borrismore Creek, MB 07B and MB 30 show a higher mean value and wider distribution of recharge values from AquiMod than GARDENIA. Whereas, with Freshford and Vickerstown, the opposite is true.

The LTA recharge calculated for each borehole show little correlation between AquiMod, GARDENIA and Metran. This is perhaps not surprising, due to the different approaches and different catchment sizes modelled by AquiMod and GARDENIA, as well as the differences in how the models operate and calculate recharge. Freshford displays a high degree of variation between average recharge values calculated by the four models, with the lowest value of 6.4 mm/month (AquiMod) and 63.0 mm/month (Metran). Borrismore Creek displays the smallest range in recharge values between the four models, with the lowest value of 15.7 mm/month (GARDENIA) and 32.9 mm/month (Metran).

There is some agreement between AquiMod and the INRM at three boreholes: at MB 30, AquiMod calculates an average recharge of 28.6 mm/month with a recharge value of 28.0 mm/month for the INRM (non-capped and capped estimate); at Borrismore Creek, AquiMod slightly underestimates average recharge at 23.7 mm/month, with a value of 24.5 mm/month for the non-capped INRM; and at Vickerstown, there is an average recharge of 10.9 mm/month for AquiMod and 7.8 mm/month for the INRM (capped and non-capped). Similarly, two of the boreholes modelled by GARDENIA also show similar average recharge values when compared with the INRM: at MB 30, GARDENIA calculates an average recharge of 24.4 mm/month which is approximately 4 mm/month less than the INRM value of 28.3 mm/month (capped and non-capped); and at Borrismore Creek, the average recharge from GARDENIA is 15.4 mm/month compared with 16.8 mm/month for the INRM (capped).



The model which consistently calculates the highest recharge value is Metran which, in most cases, is roughly 10-20 mm/month greater than the next highest model. Most of the LTA recharge values calculated from GARDENIA boreholes are lower than those calculated from Aquimod, with the exception of Freshford (45.7 mm/month) and Vickerstown (35.0 mm/month) which are both much higher than the recharge values from Aquimod (6.4 and 10.9 mm/month, respectively).

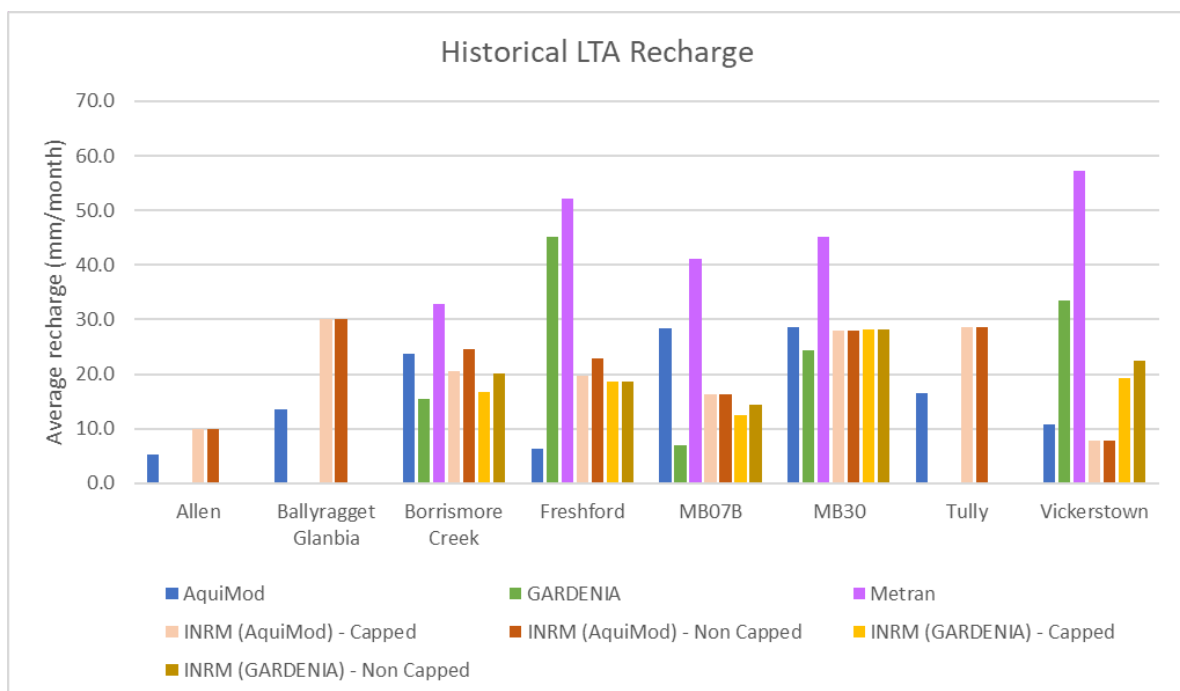


Figure 14 : Comparison of historical Long Term Average (LTA) recharge values for each site per model. Comparing Aquimod, GARDENIA, the Irish National Recharge Model (INRM) & Metran models. Different estimations of recharge from the INRM were calculated to accommodate the different catchment sizes modelled in Aquimod and GARDENIA. Ballyragget Glanbia (GARDENIA) was removed due to poor NSE scores.

Table 8: Simulated historical recharge time series produced by Aquimod (top) and GARDENIA (bottom). Note the differing y-axis scales between the Aquimod and GARDENIA graphs for Borrismore Creek, Freshford–Johnstown Rd, MB 07B (Upper). Models which failed calibration tests have not been displayed.

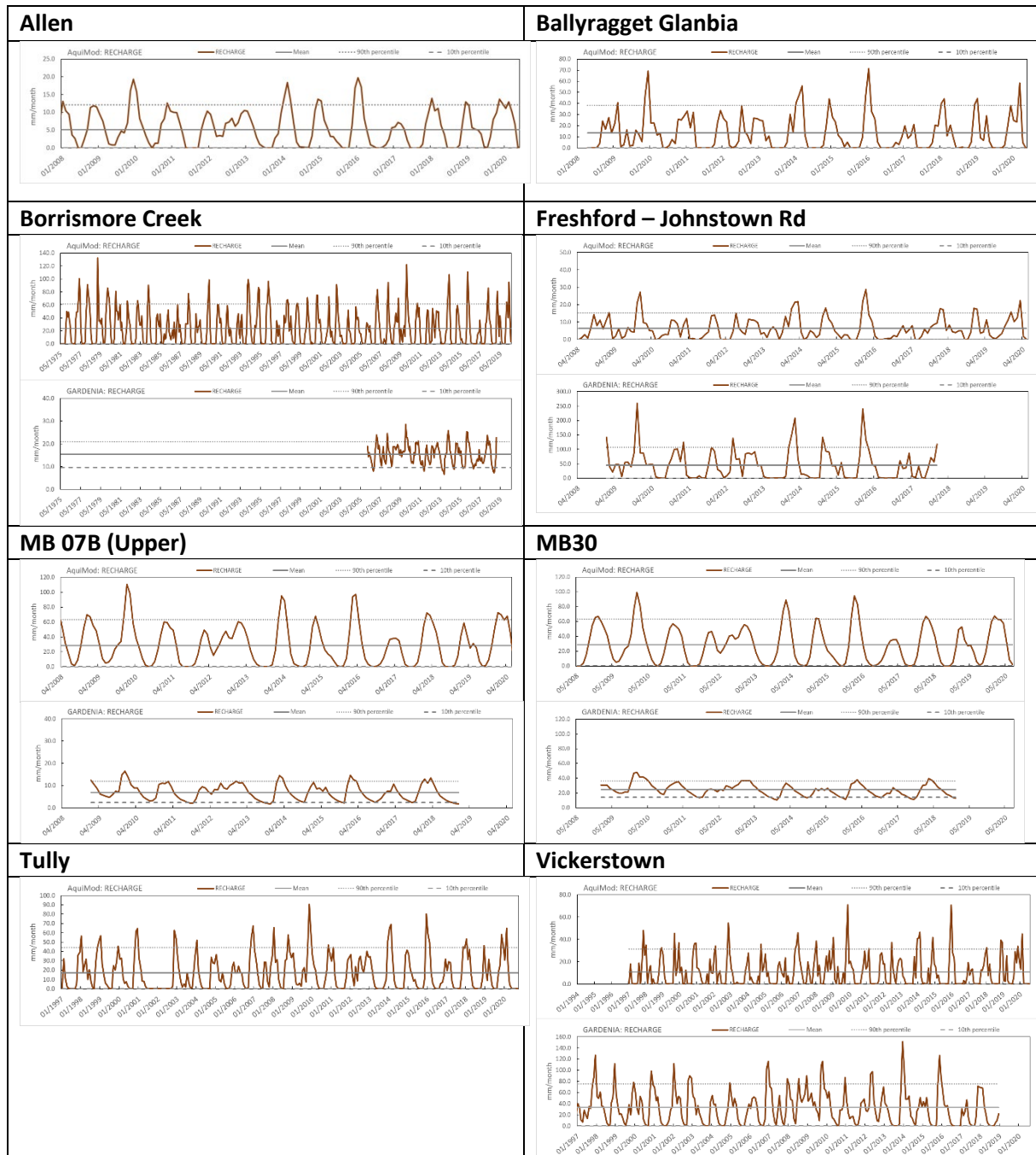
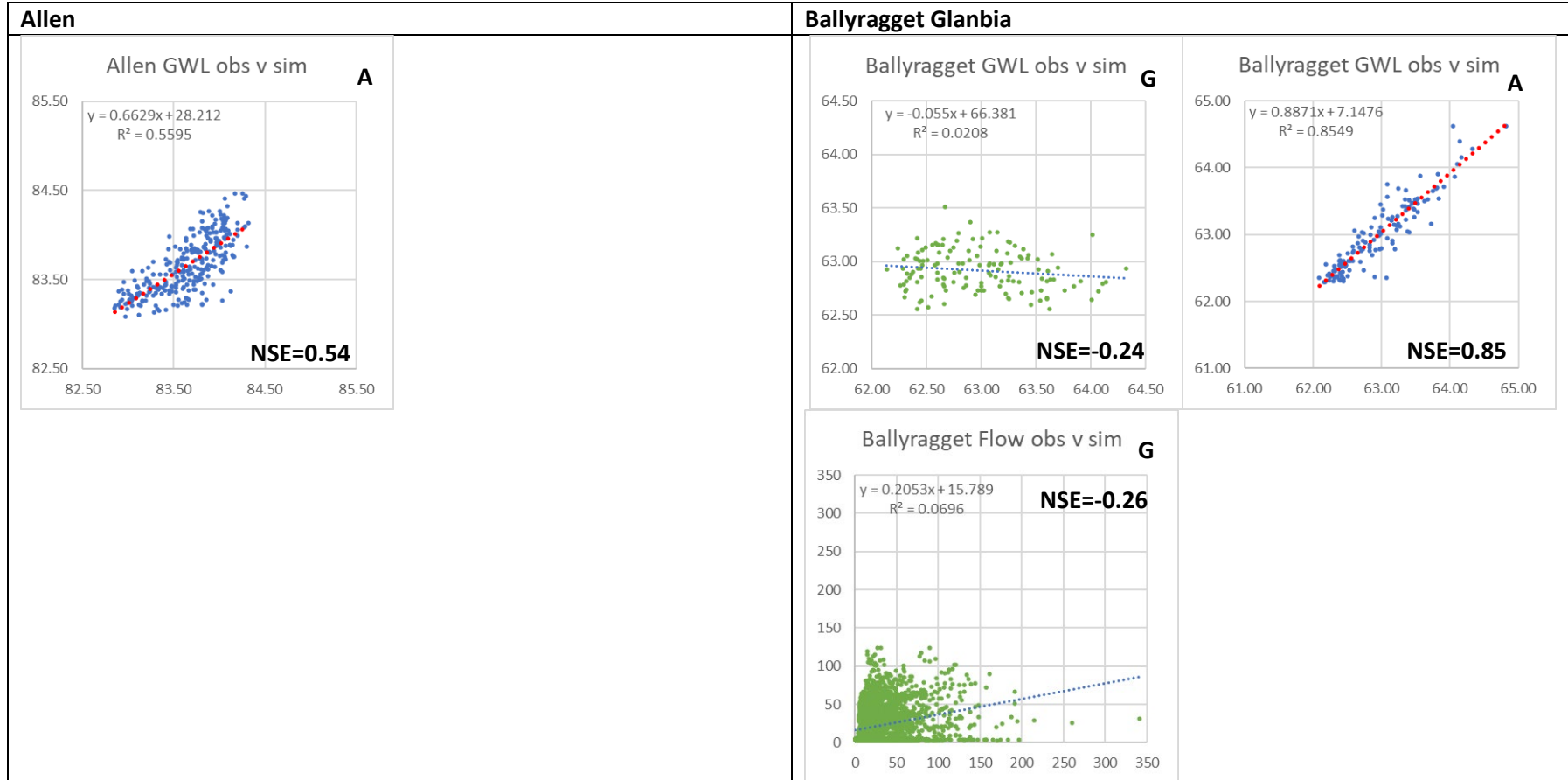
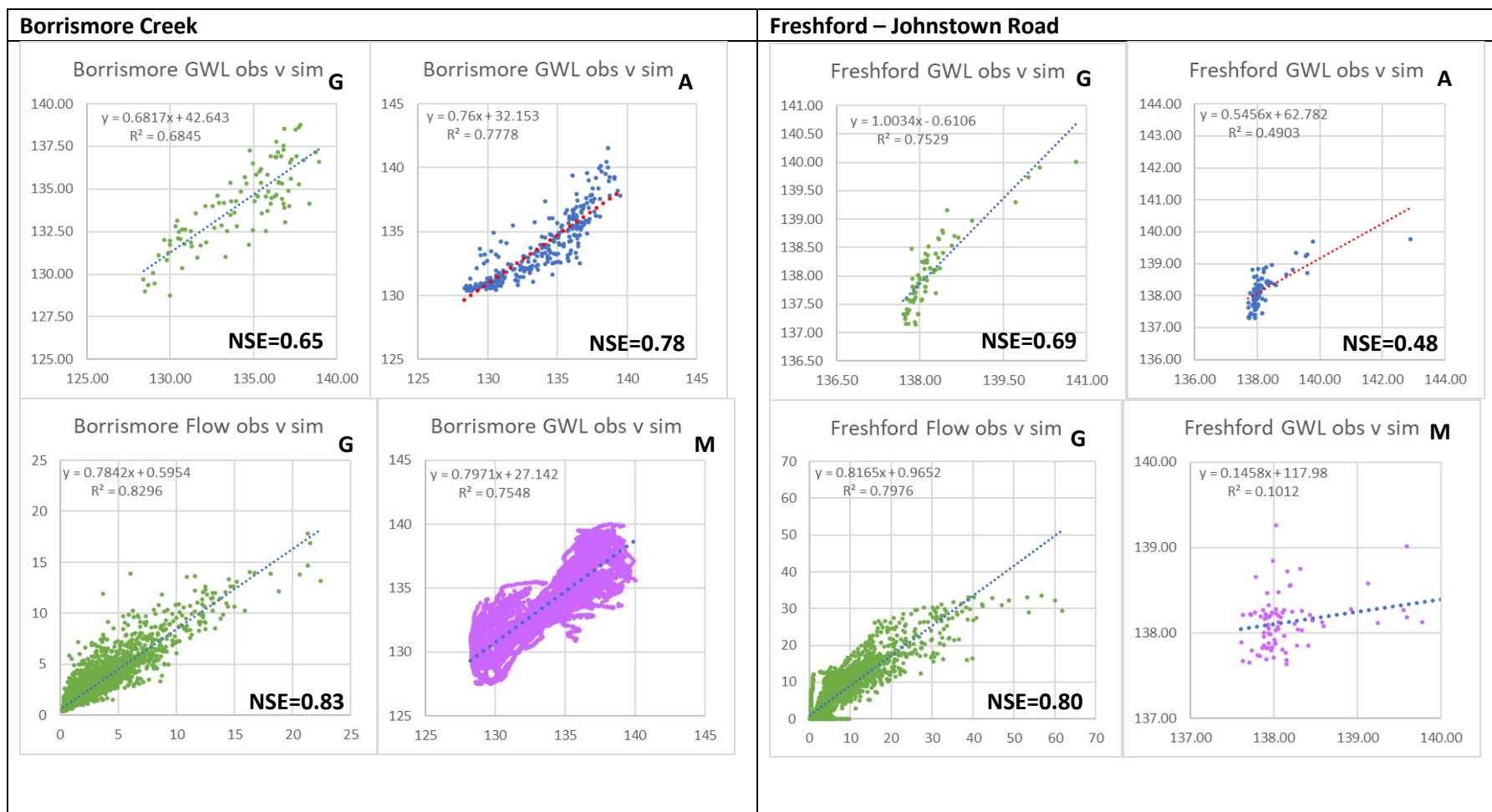
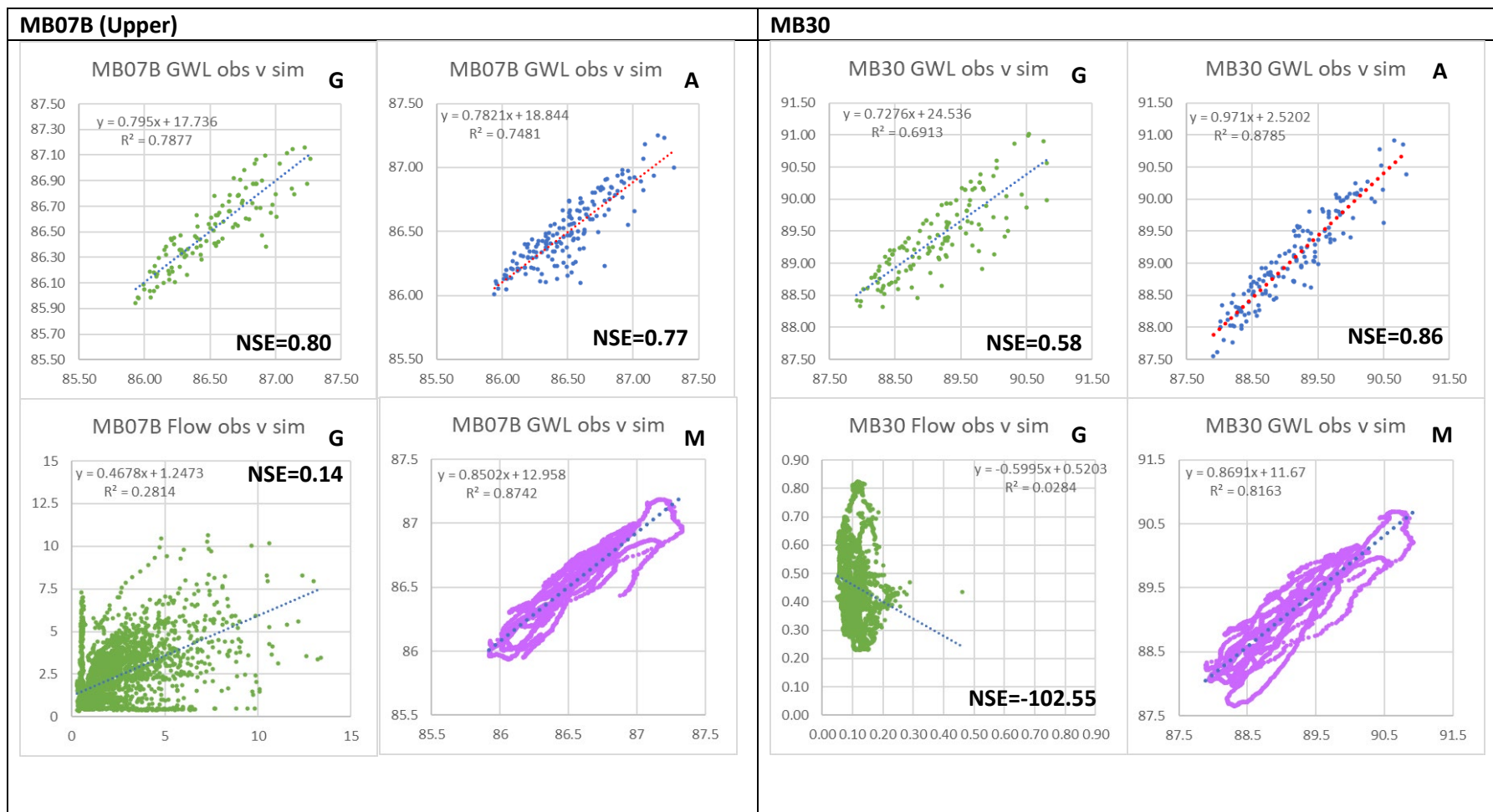
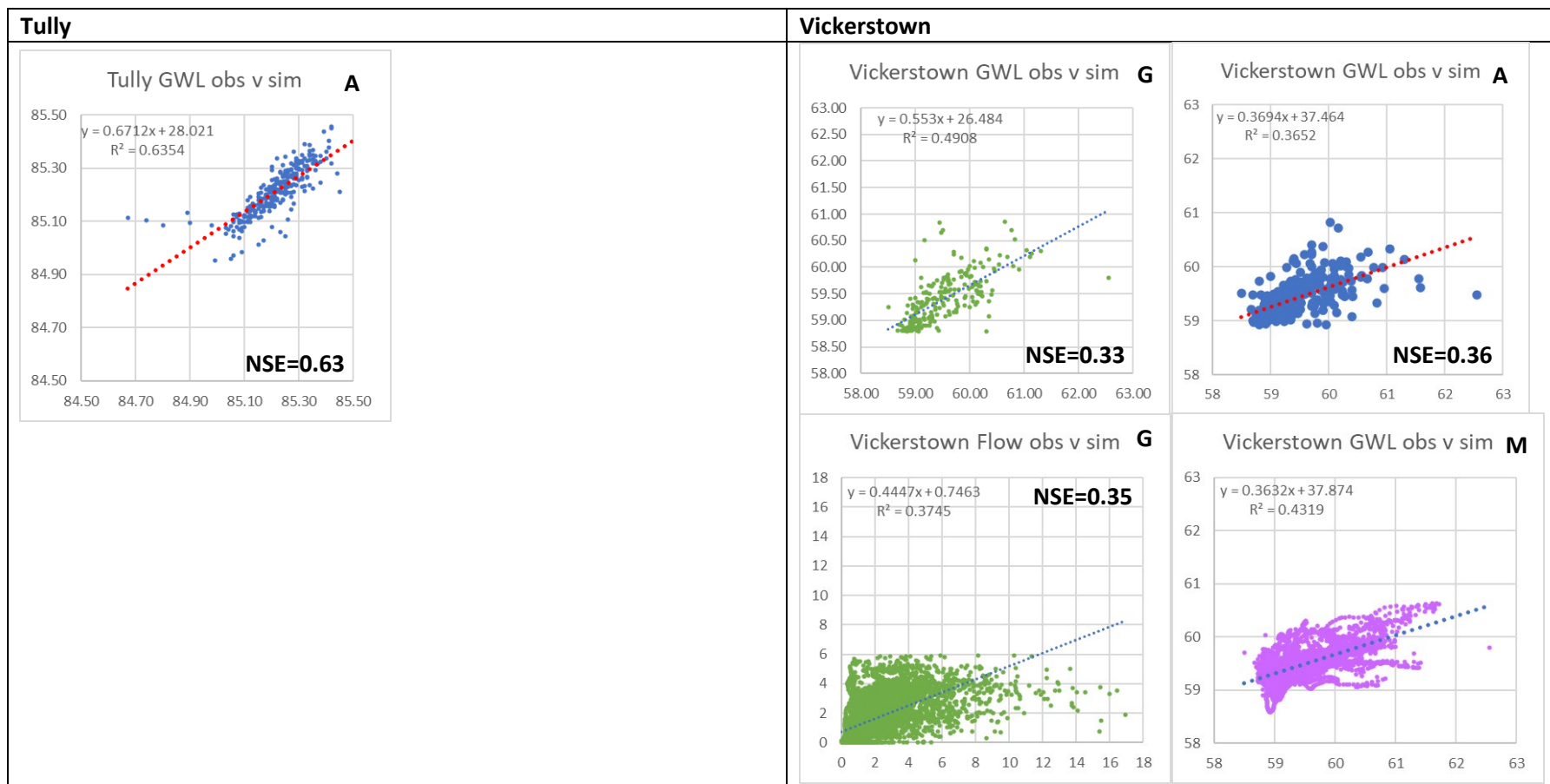


Figure 15: Scatterplots of observed groundwater levels (GWL) and river discharges (Flow, GARDENIA only) compared to the simulated results in AquiMod, GARDENIA and Metran. Blue points ("A"): AquiMod; green points ("G"): GARDENIA; pink points ("M") are Metran.









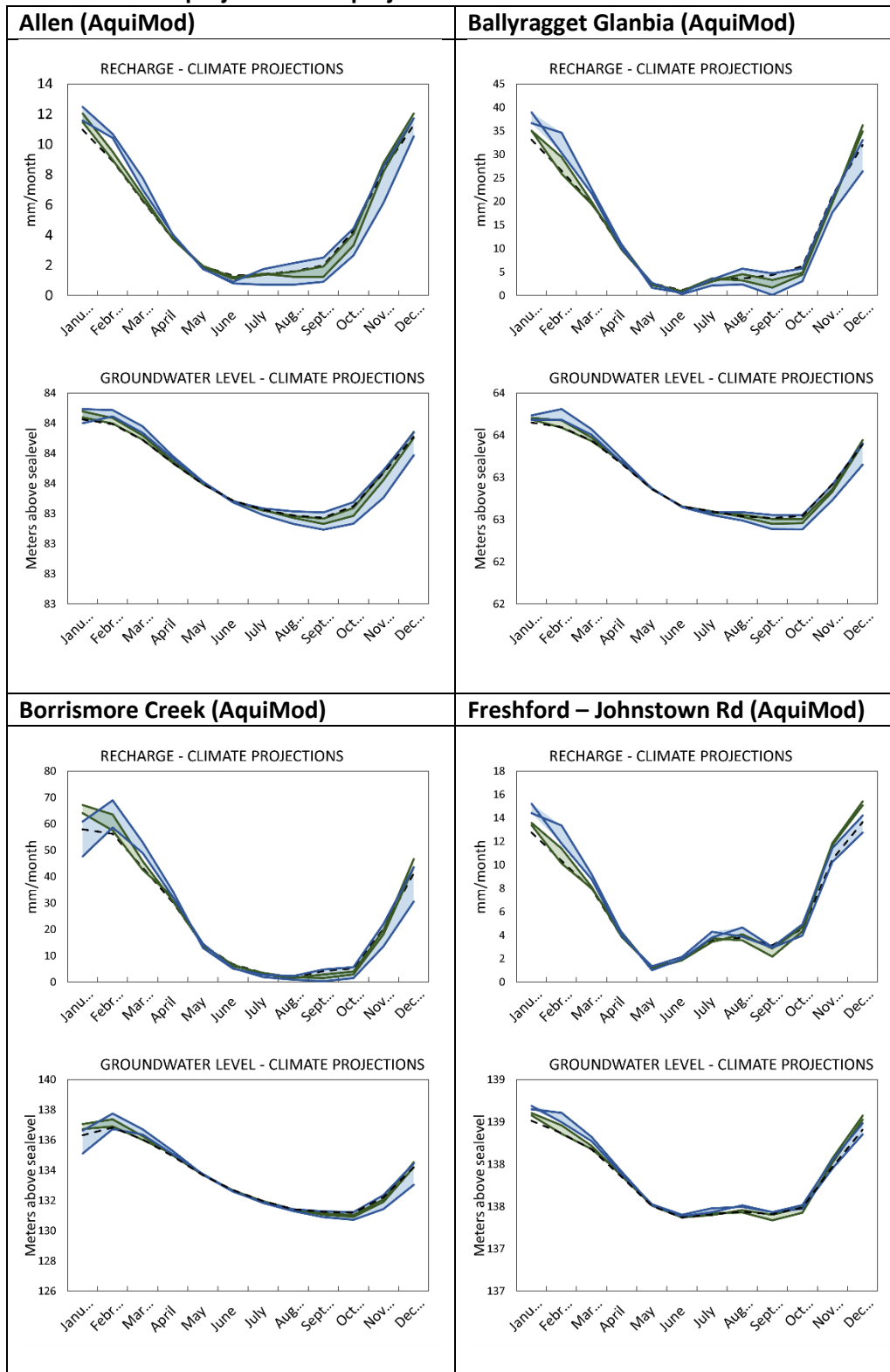
5.2 Projected recharge values

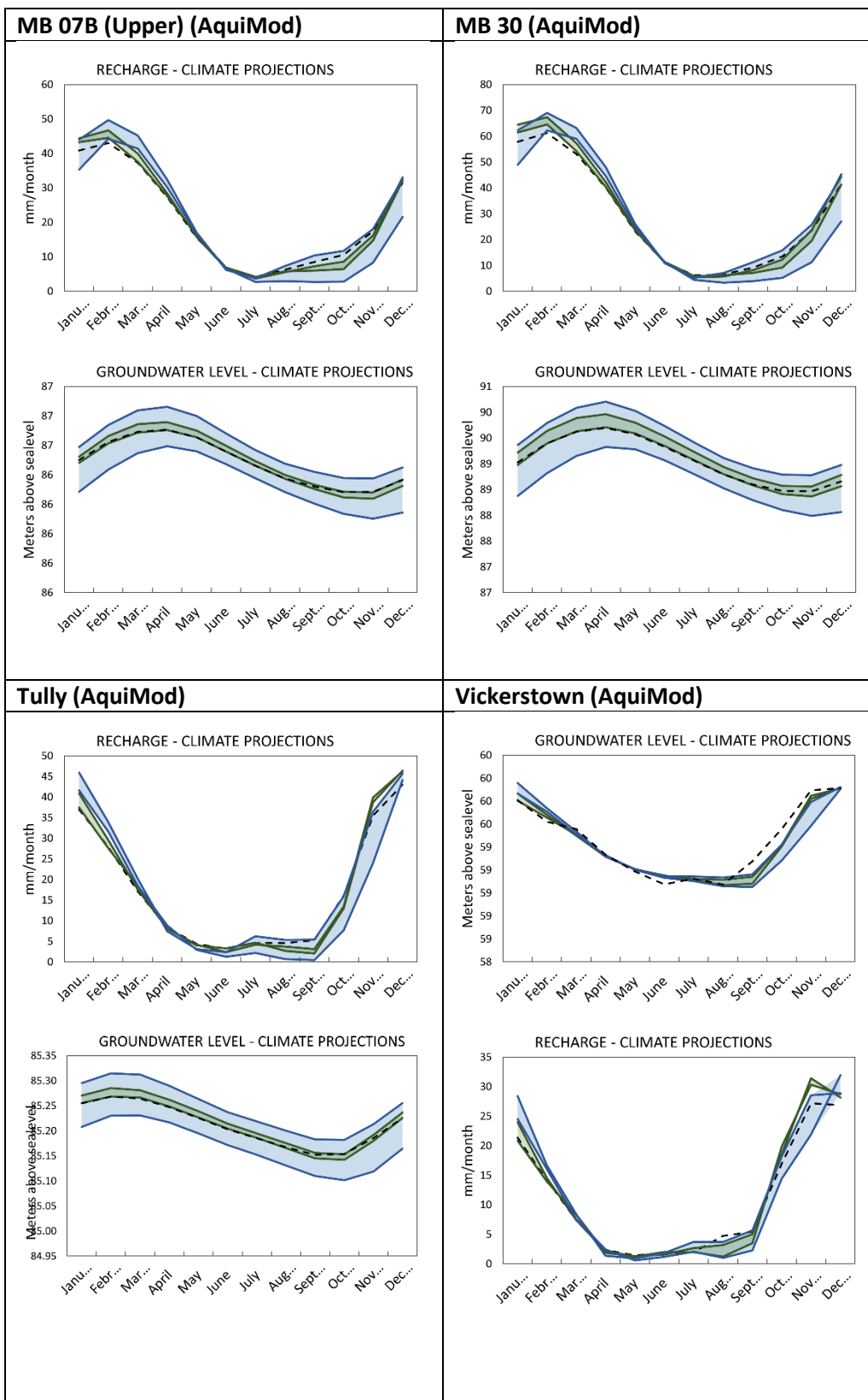
The forcing data, rainfall and potential evaporation, are altered using the change factors of the climate models (see **Table 3**). These change factors are used as multipliers to both the historical rainfall, potential evaporation and, in the case of Metran, evaporation values.

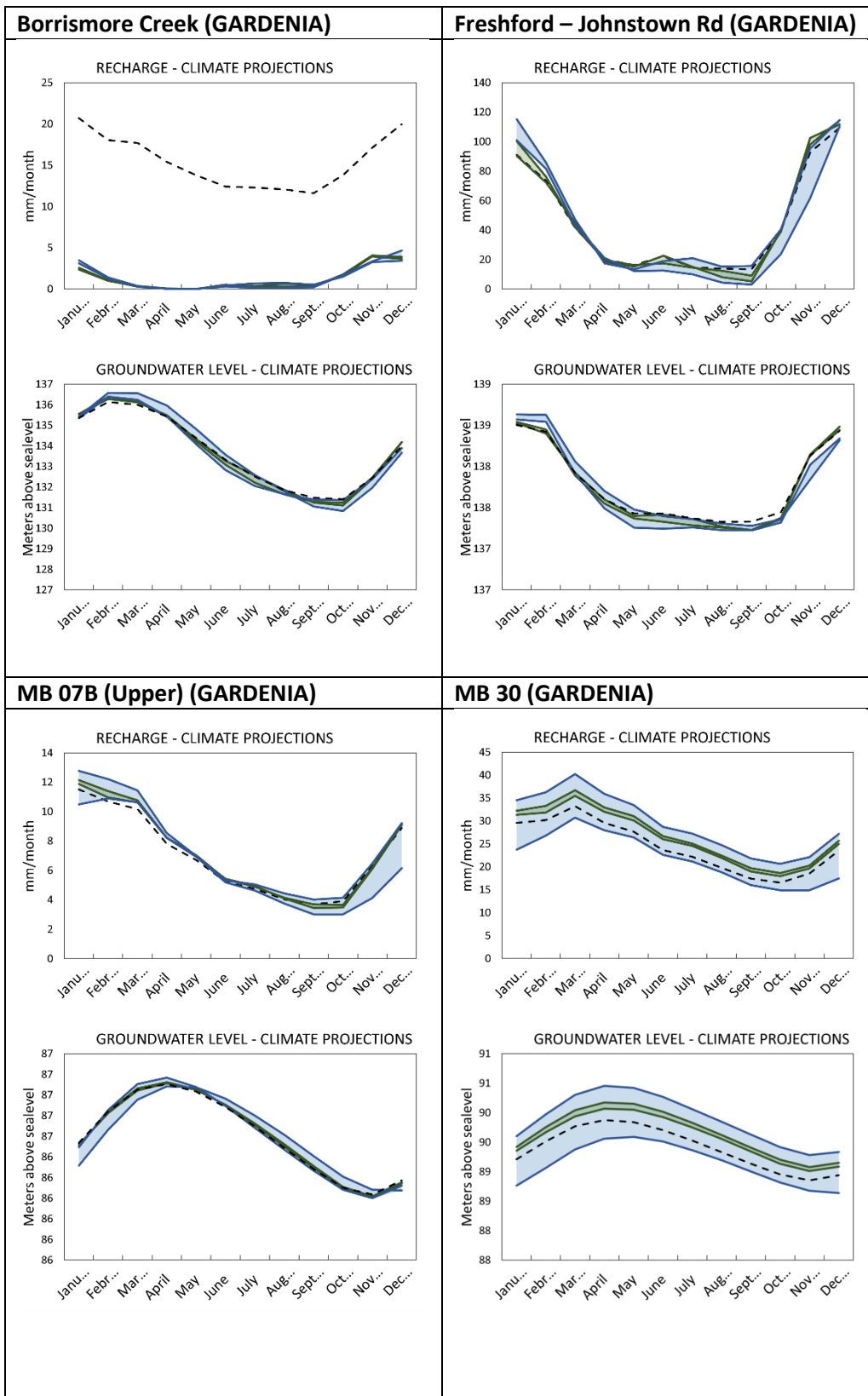
For the application involving Aquimod and GARDENIA, these factors are used to alter the time series of historical rainfall and potential evaporation values used to drive the model. When using Metran, the historical time series are altered using these factors first, and then the long-term average rainfall and evaporation values are calculated. The recharge coefficient f_c (**Appendix B**) values of the different boreholes, as calculated from the calibration of Metran model using the historical data, are then applied to calculate the projected long-term average recharge values.

Table 9 (below) shows the results of applying climate projections within Aquimod and GARDENIA. Typically, the range of projected recharge observed at each borehole is much smaller from April to June/July. During this time of the year, potential evaporation increases as temperature increases, and begins to exceed precipitation. A soil moisture deficit occurs as a result and precipitation is, therefore, taken up by this deficit which results in less precipitation entering the groundwater system as recharge. Conversely, as potential evaporation begins to drop in the mid-to-late summer, precipitation increases and exceeds potential evaporation with an eventual peak around December-January. It is during these months that we see the range in projected recharge across the different warming scenarios increase. Therefore, in Ireland, this period of the year is responsible for providing the greatest potential change to recharge.

Table 9: Predicted average monthly recharge and groundwater levels using AquiMod and GARDENIA and project climate projections







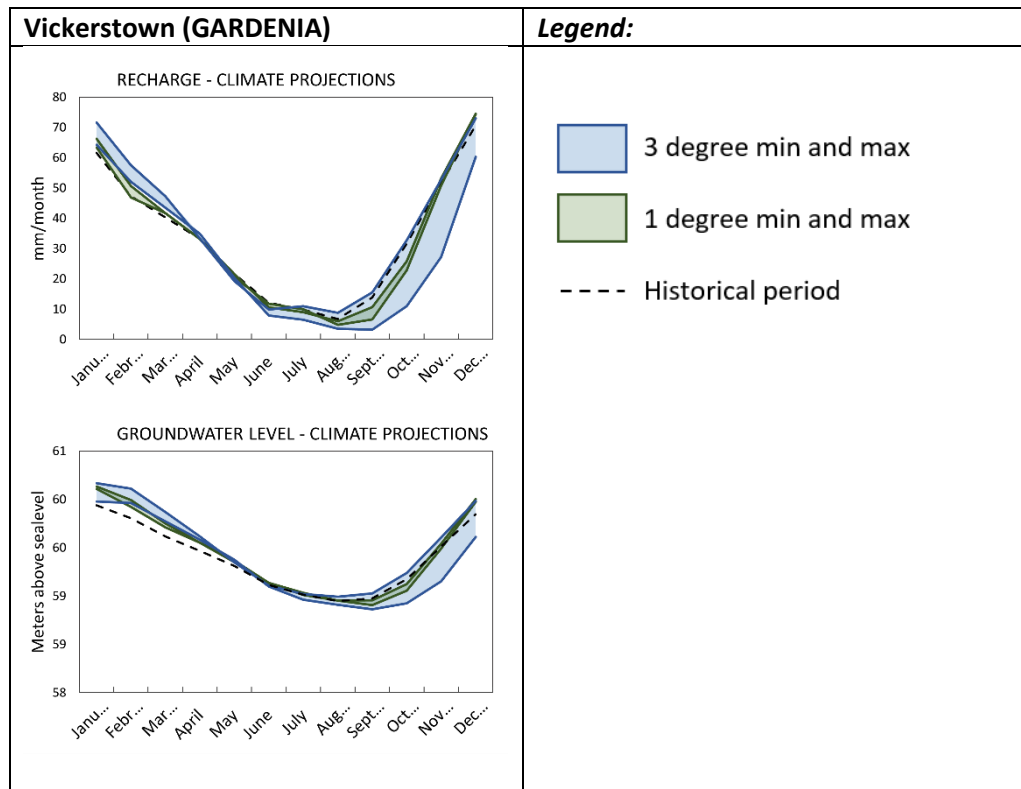


Table 10 shows the historical and projected long-term average recharge values calculated using the best performing AquiMod, GARDENIA, and Metran models and the 1°C and 3°C minimum and maximum warming scenarios outlined previously.

Figure 16 shows the historical and future long-term average recharges values calculated using the best performing AquiMod model. The greatest increase in recharge values is consistently observed when the 3°C maximum rainfall and potential evaporation data are used. The greatest reduction in recharge values is observed when the 3°C minimum rainfall and potential evaporation data are used, with the exception of Freshford which displays a 5.3% increase in recharge.

The 1°C minimum scenario shows the smallest magnitude of change to recharge, but the most variation with regards to positive or negative changes. The boreholes in the north of the study area (see **Figure 1**) show a reduction in recharge values. This includes all the boreholes situated in the Curragh gravel aquifer (MB 07B -1.3%, MB 30 -0.6%, and Tully -0.4%), a poorly productive fractured limestone aquifer (Allen -1.7%), and a karst limestone aquifer (Ballyragget Glanbia 1.0%). Contrastingly, the boreholes located in the central part of the study area, within karst limestone aquifers (Borrismore Creek +1.1%, Freshford +2.6%, and Vickerstown +1.6%) all show an increase in recharge values.

When the 1°C maximum rainfall and potential evaporation data are used, seven of eight AquiMod models display an increase in recharge, with the greatest increase observed at



Borrismore Creek (7.2%) and the smallest increase at Tully (2.9%). The exception to this increase in recharge is observed at MB 07B, which exhibits a -24.2% reduction.

Simulated historic and climate projection recharge values calculated by GARDENIA are displayed in **Figure 17**. Similar to the Aquimod results, the highest increase in recharge values is observed across all boreholes when using the 3°C maximum rainfall and potential evaporation data (excluding the anomalous projected values for Borrismore Creek). Conversely, the greatest reduction in recharge values is observed when the 3°C minimum climate scenario data was used (**Table 10**). (Excluding Borrismore Creek, as an error seems to have occurred here. No changes have been made to the input parameters, so it is unusual why the future recharge predictions are so low.)

The 1°C minimum scenario also results in the most variation with positive or negative changes to recharge values. However, when compared to Aquimod, the pattern of the percentage increase or decrease at boreholes is reversed, with the gravel aquifers in the north of the pilot area showing an increase in recharge and the karst aquifers in the middle of the pilot area showing a decrease in recharge. The highest increase in recharge is observed at MB 30 (+7.9%) and the smallest increase is observed at MB 07B (+1.8%). The greatest reduction in recharge is observed at Vickerstown (-2.5%), with the smallest reduction in recharge value observed at Freshford (-0.6%).

The 1°C maximum climate scenario results in consistent increases to recharge values for all boreholes modelled in GARDENIA, with most of the boreholes showing a ~1-4% increase in recharge and MB 30 yielding an +11.2% increase.

Similar patterns are observed with the simulated and climate projection recharge values calculated from Metran data (**Figure 18**). The use of the 3°C maximum climate scenario data results in the highest increase in recharge values across most of the boreholes, with an increase of 8.4-11.6% observed. Freshford observes a reduction of -10.4%. All boreholes modelled in Metran with the 3°C minimum climate scenario show a reduction in recharge, with values ranging from -4.0% to -22.7% (Vickerstown and Freshford, respectively).

The Metran data modelled with the 1°C minimum climate scenario data mostly follows a trend like that of GARDENIA which opposes the positive/negative changes to recharge values observed by Aquimod, with the exception of MB 07B which shows the same 1.3% decrease in recharge as Aquimod. The highest reduction is observed at Freshford (-18.5%) and the smallest reduction is observed at Vickerstown (-0.5%).

Like Aquimod and all but one of the GARDENIA models, most boreholes modelled in Metran using the 1°C maximum climate scenario data showed an increase in recharge values, with the highest increase observed at MB 30 (+5.4%) and the smallest increase at Borrismore Creek (+1.6%). Freshford displayed a -15% reduction in recharge.

Table 10: Simulated LTA historical recharge compared with simulated LTA projected recharge for the different climate change scenarios.

		Historical mm/month	1deg min mm/month	% change	1 deg max mm/month	% change	3 deg min mm/month	% change	3 deg max mm/month	% change
Allen	AquiMod	5.16	5.07	-1.7	5.38	4.3	4.50	-12.7	5.41	4.7
Ballyragget Glanbia	AquiMod	13.54	13.40	-1.0	13.99	3.3	12.89	-4.8	14.92	10.2
BMC	AquiMod	23.72	23.99	1.1	25.44	7.2	21.32	-10.1	26.38	11.2
	GARDENIA	15.66	1.29	-91.8	1.31	-91.6	1.34	-91.4	1.34	-91.5
	Metran	32.89	32.35	-1.7	33.42	1.6	28.82	-12.4	36.06	9.6
Freshford	AquiMod	6.38	6.55	2.6	6.81	6.6	6.73	5.3	7.20	12.8
	GARDENIA	45.65	45.39	-0.6	46.72	2.3	40.37	-11.6	50.01	9.5
	Metran	63.04	51.37	-18.5	53.59	-15.0	48.72	-22.7	56.46	-10.4
MB 07B (Upper)	AquiMod	28.44	28.07	-1.3	21.57	-24.2	24.98	-12.2	31.66	11.3
	GARDENIA	6.98	7.11	1.8	7.23	3.6	6.42	-8.0	7.56	8.3
	Metran	41.08	40.52	-1.3	42.18	2.7	36.71	-10.6	44.89	9.3
MB 30	AquiMod	28.59	28.40	-0.6	30.16	5.5	25.25	-11.7	32.00	11.9
	GARDENIA	24.32	26.23	7.9	27.06	11.2	21.78	-10.4	29.39	20.8
	Metran	45.13	45.60	1.0	47.55	5.4	42.15	-6.6	50.26	11.4
Tully	AquiMod	17.11	17.04	-0.4	17.60	2.9	15.21	-11.1	18.86	10.2
Vickerstown	AquiMod	10.88	11.06	1.6	11.56	6.2	10.43	-4.2	12.11	11.2
	GARDENIA	34.98	34.11	-2.5	35.61	1.8	30.25	-13.5	38.18	9.2
	Metran	57.31	57.03	-0.5	59.48	3.8	54.99	-4.0	62.15	8.4



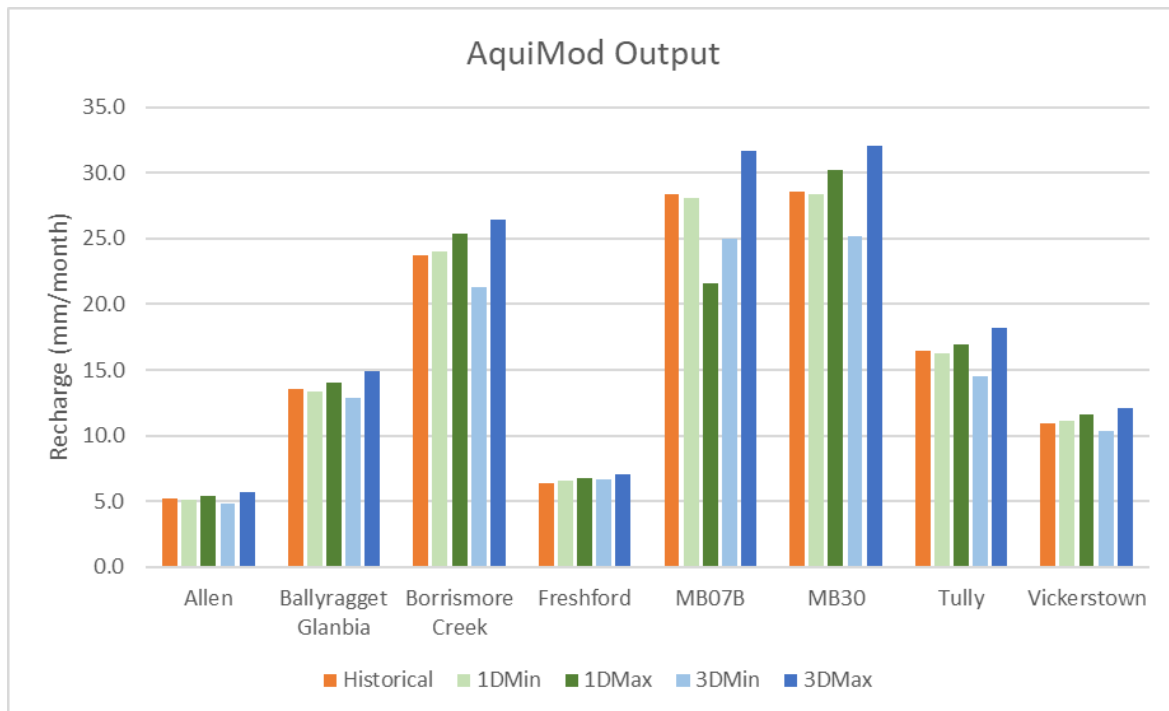


Figure 16: Historical/simulated and future recharge values as produced by the best performing AquiMod model

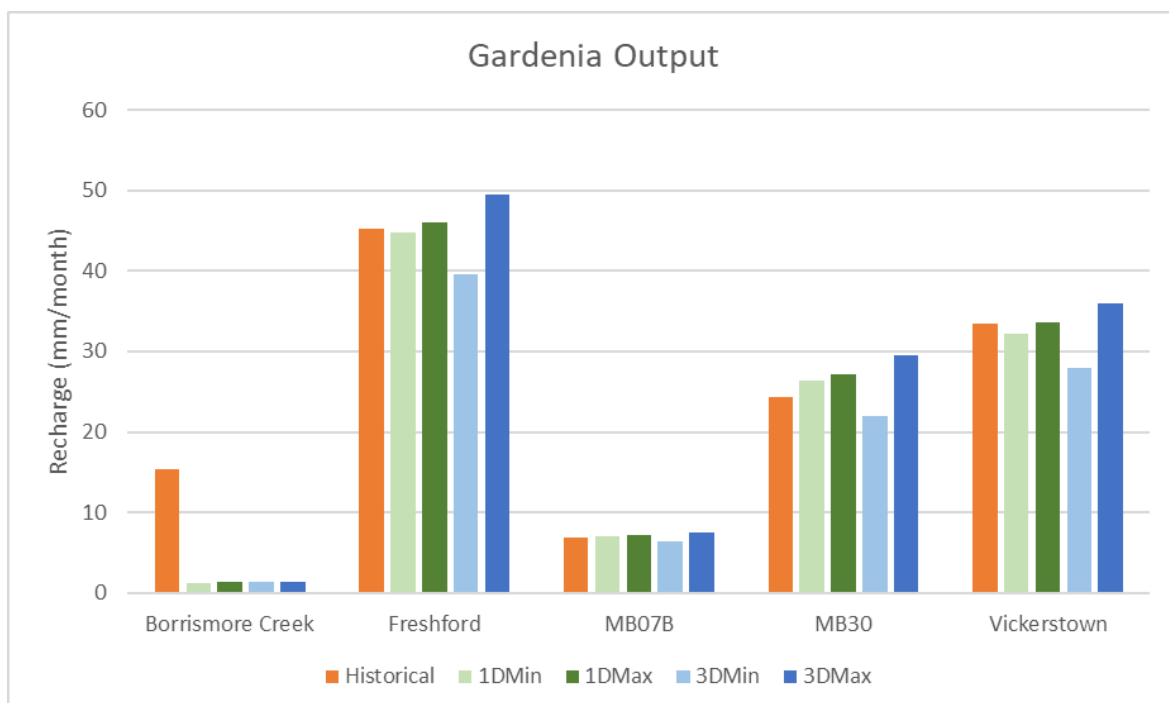


Figure 17: Historical/simulated and future recharge values as produced by the best performing GARDENIA model. Note that no future predictions were modelled for Ballyragget Glanbia due to poor NSE scores.



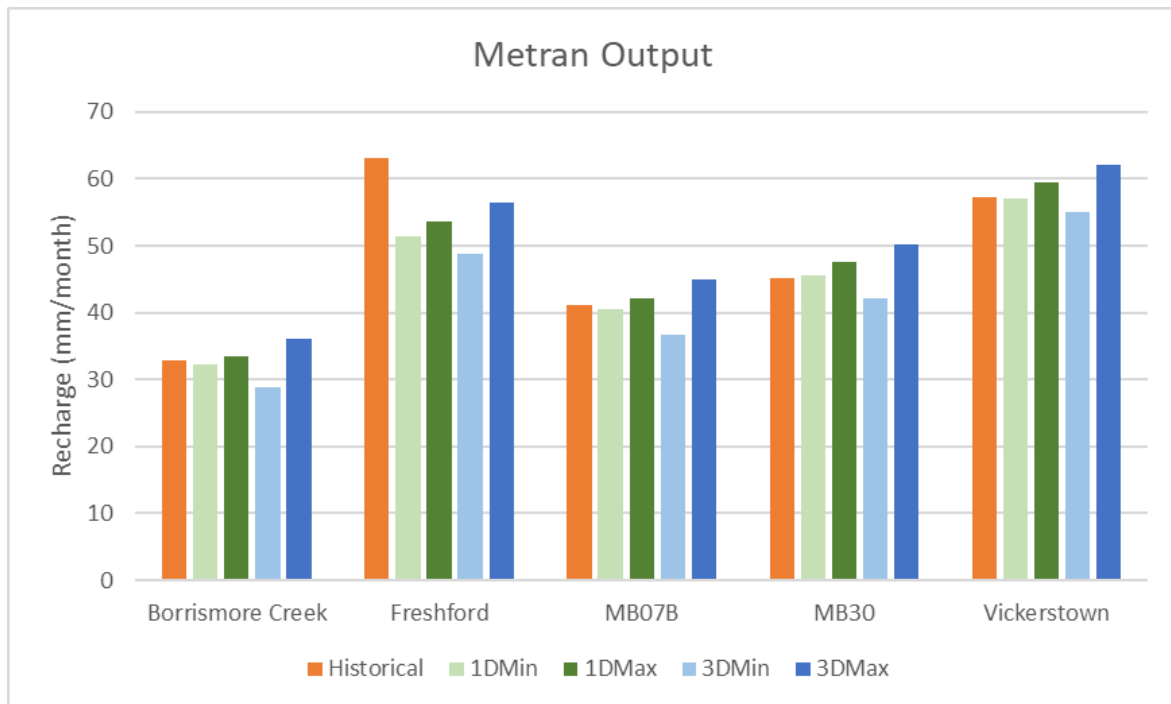


Figure 18: Historical/simulated and future recharge values as produced by the best performing Metran model.

It is evident that trends are observed with regards to relative increases or decrease to recharge values observed for most of the climate scenarios. The greatest consistent reduction in recharge across all models is observed when the 3°C minimum rainfall and potential evaporation data are used, with the exception of Freshford (AquiMod) which displays a 5.3% increase in recharge.

The greatest increase in recharge values across all models is observed when the 3°C maximum rainfall and potential evaporation data are used, with the exception of Freshford (Metran) which shows a 10.4% decrease in recharge. Similarly, when the 1°C maximum rainfall and potential evaporation data are used, the GARDENIA models, Metran models (excluding Freshford), and AquiMod models (excluding MB 07B) all show an increase in recharge values.

When the 1°C minimum climate scenario data are used, there are no clear trends observed when comparing results from the three models.

It is also evident that there are few similarities between the amounts of calculated LTA recharge across all climate scenarios from each model. For example, recharge calculated from Metran is, roughly 10-20 mm/month greater than that of the next highest recharge value from another model.

Excluding the modelling of Borrismore Creek in GARDENIA which has yielded anomalously low results, the Freshford data displays the most variation across the models and climate



scenarios, with some calculated recharge values contradicting otherwise relatively consistent results from other boreholes in the same climate scenario. For example, Freshford (Metran) is the only model which shows a reduction in recharge in the 3°C max scenario, with Freshford (AquiMod) being the only model which predicts a recharge increase in the 3°C min scenario. This may have been a result of sparse groundwater level observations due to a sump in the bottom 1.2 m of the Freshford borehole which caused inaccurate groundwater level readings, and model assumptions not representing the groundwater system sufficiently well.

As previously mentioned, there appears to be an issue with the GARDENIA – Borrismore Creek 'Recharge – Climate Projections' graph shown above. This anomaly is unusual as no parameters have been changed from the historical simulated recharge predictions to the future projections scenarios. All delta change functions calculations have been double checked and there does not appear to be any errors in the daily to monthly recharge conversions. As such, we can suggest that this result is due to some sort of scaling error in the graphs, as the 1C and 3C projections follow a similar trend to that of the historical period, albeit at a reduced scale.

6 REFERENCES

Archer, J.B., Sleeman, A.G. and Smith, D.C., 1996. *A Geological Description of Tipperary and Adjoining Parts of Laois, Kilkenny, Offaly, Clare and Limerick – to accompany the Bedrock Geology 1:100,000 Scale Map Series; Sheet 18, Tipperary*, with contributions by K. Claringbold, G. Staley (Mineral Resources) and G. Wright (Groundwater Resources). Geological Survey of Ireland, Dublin, Ireland. 76 pp.

Ball, D., 2010. What will the Impacts of Climate Change be for Groundwater Systems in Ireland? Proceedings of the 30th Annual Conference of the IAH (Irish Group), Groundwater in the Hydrological Cycle – Pressures and Protection. Tullamore, Ireland, 20-21 April, 2010.

Cawley, A., 1990. The Hydrological Analysis of a Karst Aquifer System. Unpublished M.Eng. Thesis. Department of Engineering Hydrology, University College Galway, Galway, Ireland.

Collins, J.F., and Cummins, T., 1996. *Agroclimatic Atlas of Ireland*. AGMET. Joint Working Group on Applied Agricultural Meteorology, AGMET, Dublin, Ireland.

Daly, E.P., 1978. Groundwater Investigations in County Laois in 1976. Groundwater Division, Geological Survey of Ireland. Internal Report Number 4. Geological Survey of Ireland, Dublin, Ireland.

Daly, E.P., 1980. The Drilling and Testing of Two Boreholes and Groundwater Development in the Westphalian Sandstones of the Slieveardagh Hills, Co Tipperary. Groundwater Division, Geological Survey of Ireland. Internal Report Number 7. Geological Survey of Ireland, Dublin, Ireland.

Daly, E.P., 1981. Case Study: The Kilmanagh River Gravels. Groundwater Division, Geological Survey of Ireland. Geological Survey of Ireland, Dublin, Ireland.

Daly, E.P., 1982. The Groundwater Resources of the Southeast Industrial Development Region. Unpublished draft report of the Geological Survey of Ireland, Dublin, Ireland.

Daly, E.P., 1990. The Likely Effects of Significant Climatic Changes on the Flow Regime in the Principal Irish Aquifers. Proceedings of 10th Annual Seminar, International Association of Hydrogeologists (Irish Group), Portlaoise, Ireland.

Daly, E.P., 1993. Hydrogeology of the Dolomite Aquifer in the Southeast of Ireland. Proceedings of 13th Annual Seminar, International Association of Hydrogeologists (Irish Group), Portlaoise, Ireland.

Daly, E.P., 1994. Groundwater Resources of the Nore River Basin. Geological Survey of Ireland Report Series RS 94/1 (Groundwater). Geological Survey of Ireland, Dublin, Ireland.

Environmental Protection Agency, 2018. Corine Landcover 2018. Available from <https://data.gov.ie/dataset/corine-landcover-2018>

Environmental Protection Agency, 2016. *EPA HydroNet*. Viewed 26 March 2021. Available from: http://www.epa.ie/hydronet/#IE_SE_G_0156_1500_0009

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1988) Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56. Food and Agriculture Organisation of the United Nations, Rome.

Flanagan, J., Nolan, P., McGrath, R. and Werner, C., 2019. Towards a definitive historical high-resolution climate dataset for Ireland – promoting climate research in Ireland. *Advances in Science and Research*, 15, pp.263-276.

GSI (Geological Survey of Ireland), 2005a. *Grouped Rock Units*. Scale 1:100,000. Geological Survey of Ireland, Dublin, Ireland.

Hunter Williams, N.H. and Lee, M., 2007. Ireland at risk - Possible implications for groundwater resources of climate change. Irish Academy of Engineering. <http://iae.ie/publications/?years=2007>

Hunter Williams, N.H., Misstear, B.D.R., Daly, D., Johnston, P.M., Lee, M., Cooney, P. and Hickey, C. (2011) A National Groundwater Recharge Map for Ireland. Proceedings of the *National Hydrology Conference 2011*. 15 November 2011, Athlone, Co. Westmeath, Ireland.

Hunter Williams, N.H., Misstear, B.D.R., Daly, D. and Lee, M., 2013. Development of a national groundwater recharge map for the Republic of Ireland. *Quarterly Journal of Engineering Geology and Hydrogeology*, **46**, 2013, pp. 493–506.

Hunter Williams, N.H., Carey, S., Werner, C. and Nolan, P. (in press) Updated National Groundwater Recharge Map, *Irish Groundwater Newsletter*.

Karlsson, I. B., Eisenbruchner, L. T., Kidmose, J., and Højberg, A. L.: National scale climate change impact assessment – investigating long-term variations in the climate change signal for groundwater levels across geologies and aquifers, *EGU General Assembly 2020*, Online, 4–8 May 2020, EGU2020-4741, <https://doi.org/10.5194/egusphere-egu2020-4741>

Kelly, C., Hunter Williams, N.H. and Misstear, B.D.R., 2015. *Irish Aquifer Properties – A reference manual and guide*. Version 1. March 2015. Geological Survey Ireland, Dublin, Ireland.

Mullarkey, E., Tedd, K., Meehan, R., Kelly, C., Pilmer, A., Doherty, D., Greene, J., O’Keeffe, M., Kabza, M., Duncan, N. and Schuler, P. (2021) Using hydrograph separation methods for catchment water balances: an output from GSI's GW3D project. Poster presented at *41st Annual IAHR Irish Group Groundwater Conference: “Catchment Science and Management – The Role of Geoscience and Groundwater”*, 26-27 April, 2021.

Nolan, P., 2015. Ensemble of regional climate model projections for Ireland. Report 2008-FS-CC-m. Prepared for the Environmental Protection Agency, Wexford, Ireland.

Robins, N.S. and Missteart, B.D.R., 2000. *Groundwater in the Celtic Regions: Studies in Hard Rock and Quaternary Hydrogeology*. Geological Society, Special Publication No. 182. pp. 5–17. The Geological Society, London, UK.

Schulte, R.P.O., Diamond, J., Finkle, K., Holden, N.M. and Brereton, A.J., 2005. Predicting the soil moisture conditions of Irish grasslands. *Irish Journal of Agricultural and Food Research* 44: 95–110.

Tedd, K., Missteart, B., Coxon, C., Daly, D., Hunter Williams, N.H., Craig, M. and Mannix, M. 2011. *Review of groundwater level data in the South Eastern River Basin District*. EPA STRIVE Programme 2007–2013. Environmental Protection Agency, Dublin.

Tedd, K., Missteart, B., Coxon, C., Daly, D., and Hunter Williams, N.H., 2012. Hydrogeological insights from groundwater level hydrographs in SE Ireland. *Quarterly Journal of Engineering Geology and Hydrogeology*, **45**, 19 –30. DOI: 10.1144/1470-9236/10-026.

Thi  ry D., 1988. Forecast of changes in piezometric levels by a lumped hydrological model. *Journal of Hydrology* 97 (1988), pp. 129-148.

Thi  ry, D., 2010. Reservoir Models in Hydrogeology. in “Mathematical Models Volume 2, chapter 13, pp. 409-418 Environmental Hydraulics Series”. Tanguy J.M. (Ed.) –   ditions Wiley/ISTE London. ISBN: 978-1-84821-154-4.

Thi  ry, D., 2013. Didacticiel du code de calcul Gard  nia v8.1. Vos premi  res mod  lisations. Rapport BRGM/RP-61720-FR, 130 p., 93 fig. (Updated v8.6)

Thi  ry, D., 2014. Logiciel GARD  NIA, version 8.2. Guide d’usage. Rapport BRGM/RP-62797-FR, 126 p., 65 fig., 2 ann. (Updated v8.6).

Thi  ry, D., 2015. Validation du code de calcul GARD  NIA par mod  lisations physiques comparatives. Rapport BRGM/RP-64500-FR, 48 p., 28 fig. (Updated v8.6).

Tietzsch-Tyler, D., Sleeman, A.G., McConnell, B.J., Daly, E.P., Flegg, A.M., O’Connor, P.J. and Warren, W.P., 1994. *Geology of Carlow–Wexford. A geological description to accompany the Bedrock Geology 1:100,000 Scale Map Series; Sheet 19, Carlow – Wexford*. Geological Survey of Ireland, Dublin, Ireland, 58 pp.

Werner, C., Nolan, P. and Naughton, O., 2019. *High-Resolution Gridded Datasets of Hydro-Climate Indices for Ireland*. EPA/GSI funded research project. 2016-W-DS-29 EPA, Wexford, Ireland.

Zaadnoordijk, W.J., Bus, S.A.R., Lourens, A., Berendrecht, W.L. (2019) Automated Time Series Modeling for Piezometers in the National Database of the Netherlands. *Groundwater*, 57, no. 6, p. 834-843. <https://onlinelibrary.wiley.com/doi/epdf/10.1111/gwat.12819>

7 ACKNOWLEDGEMENTS

Willem Zaadnoordijk from TNO kindly ran all of the Metran models (historic and future climate scenarios) for the Irish groundwater level observations used in this study.

Majdi Mansoor from BGS was very generous with his time in helping us to start using AquiMod and to develop successful model runs.

Hélène Bessiere from BRGM was very generous with her time in helping us to get going with GARDENIA and to better understand the model parameters and set up.

APPENDICES

APPENDIX A – groundwater monitoring points in SE region pilot area

From Tedd *et al.*, 2011.

Table 1. Historic groundwater level monitoring points (MPs).

Name	GSI (EPA) MP code	County	X	Y	Geology	Aquifer type ²	Subsoils	Subsoil permeability	Vulnerability	Operator	Type of MP	Type of monitoring	Start date	End date	Depth (mbgl)	Datum (maOD)
Oldtown	Kny 18/92 (10_013)	Kilkenny	238700	154400	Sand and gravel	Rg	18 m sand & gravel	H	E	GSI/OPW	BH	Chart recorder to Mar-08, then logger	Oct-80	Ongoing	20	118.45
Kilmeague		Kildare	278900	223700	Sand and gravel	Lm	Sand & gravel	H	H	GSI	BH	Manual dips	Jun-70	Jul-88	27.4	~107
Rahilla		Kildare	271420	271420	Till with gravel	Rg	Till with gravel	H	H	GSI	DW	Manual dips	Nov-68	Oct-87	35.4	~124
Ballincurry	Tip 55/65	Tipperary	227800	148500	Westphalian Sst	Lm	6 m clay; down-gradient of Rck	L	HL	GSI	BH	Chart recorder	Oct-77	Oct-82	60	170.35
Woodsgriff/Borrismore Creek	Kny 12/8 (10_005)	Kilkenny	233000	161500	Karstified Imst	Rkd	0–3 m TLs	M	E	GSI/OPW	BH	Chart recorder to Oct-07; then logger	Apr-75	Ongoing	36	147.34
Tubrid Lower	Kny 12/34	Kilkenny	23423	16192	Karstified Imst	Rkd	0–3 m TLs	M	E	GSI		Chart recorder	Aug-71	Dec-91	12.7	128.12
Clomantagh Lower	Kny 13/42	Kilkenny	234600	163800	Karstified Imst	Rkd	3–10 m TLs; close to KaRck	M	H	GSI		Chart recorder	Jul-74	Oct-94	57	149.39
Cullahill	Kny 35/39	Laois	237400	175700	Karstified Imst	LI	3–10 m TLs; alluvium	M	H	GSI/OPW			Sep-76	Jun-09	–	~85
Masterson		Laois	261600	193100	Karstified Imst	Rkd	3–10 m TLs; alluvium	M	H	GSI	DW	Manual dips	Nov-70	Oct-90	14	~105
Land Commission 2		Laois	259300	193100	Karstified Imst	Rkd	0–3 m TLs; close to KaRck	M	E	GSI	BH	Manual dips	Jul-71	Jan-81	–	~159
Rathduff	Kny 27/58 (10_017)	Kilkenny	250500	143300	Dolomitised Imst	Rkd	18 m TLs	M	H	GSI/OPW	BH	Chart recorder to Mar-08, then logger	Aug-81	Ongoing	62	46.75
Boston Co. Co.		Kildare	271900	220400	Dolomitised Imst	LI	Rck	–	X	GSI	DW	Manual dips	Apr-70	Aug-85	15.9	~119
Granston Manor	Ls 28/168	Laois	234100 ¹	178600	Crosspatrick Fm	LI	6.8 m clay; 1.4 m sand	M	H	GSI/Arcon	BH	Chart recorder	Sep-78	Jul-96	30	84.57
Ardscull DW		Kildare	272200	198700	Ballysteen Fm	LI	0–3 m TLs; close to Rck	–	E	GSI	DW	Manual dips	Jul-69	Oct-90	18.9	~89
Knocktopher Manor	Kny 31/72 (10_012)	Kilkenny	253140	135930	Kiltorcan Sst	Rf	5 m TLs	L	E	GSI/OPW	BH	Chart recorder to May-08; then logger	Aug-80	Ongoing	40	61.67

¹The co-ordinates of the Granston Manor fall within a lake, the actual location of the boreholes is likely to be close to this lake; ~, approximate elevations were taken from the appropriate Ordnance Survey Ireland Discovery Series (1:50,000) map.

²For aquifer type codes, please refer to Box 5.1.

Sst, sandstone; Imst, limestone; FM, Formation; Rck, bedrock outcrop and subcrop; TLs, tills derived chiefly from limestone; KaRck, karstified limestone bedrock outcrop or subcrop; H, High; M, Moderate; L, Low; E, Extreme; HL, High to Low (only interim data available); GSI, Geological Survey of Ireland; OPW, Office of Public Works; EPA, Environmental Protection Agency; BH, borehole; DW, drinking water; mbgl, metres below ground level; maOD, metres above Ordnance Datum.

Table 1 Environmental Protection Agency (EPA) Water Framework Directive monitoring programme monitoring points (MPs).

Name	EPA (GSI) MP code	County	X	Y	Start date	End date	Type of MP	Type of monitoring	Geology	Depth of borehole (mbgl)	Datum (maOD)	Operator
Oldtown	10_013 (Kny 18/92)	Kilkenny	238700	154400	Oct-80	Ongoing	BH	Chart recorder to Mar-08, then logger	Sand and gravel	20.00	118.45	GSI/OPW
Ballyragget Glanbia Factory	10_002	Kilkenny	244002	172803	Mar-08	Ongoing	BH	Logger	Sand and gravel	18.00		EPA/LA
Ballysax	09_002	Kildare	280278	210832	Jun-08	Ongoing	BH	Logger	Sand and gravel	18.00		EPA/LA
Brownstown	09_004	Kildare	278639	210092	Jun-08	Ongoing	BH	Logger	Sand and gravel	13.00		EPA/LA
Landfill Site	01_004	Carlow	270647	170052	Mar-08	Ongoing	BH	Logger	Sand and gravel	69.00		EPA/LA
PF – MB29	09_011	Kildare	275043	213065	Apr-08	Ongoing	BH	Logger	Sand and gravel	13.30		EPA/LA
PF – MB30	09_012	Kildare	275042	213190	Apr-08	Ongoing	BH	Logger	Sand and gravel	24.00		EPA/LA
PF – MB37	09_013	Kildare	277433	217126	Jun-08	Ongoing	BH	Logger	Sand and gravel	18.20		EPA/LA
PF – S10	09_017	Kildare	276426	215904	No data	No data	BH		Sand and gravel	–		EPA/LA
PF – SB31	09_018	Kildare	276423	215894	No data	No data	BH		Sand and gravel	9.00		EPA/LA
PF – MB7 (Lower)	09_016	Kildare	276810	215540	May-08	Ongoing	BH	Logger	Sand and gravel			EPA/LA
PF – MB7 (Middle)	09_015	Kildare	276810	215540	May-08	Ongoing	BH	Logger	Sand and gravel			EPA/LA
PF – MB7 (Upper)	09_014	Kildare	276810	215540	May-08	Ongoing	BH	Logger	Sand and gravel			EPA/LA
PF – Hangedman's Arch	09_010	Kildare	275916	217539	No data	No data	Spring		Sand and gravel			EPA/LA
Kyle Public Water Supply	11_008	Laois	255501	192243	Jan-77	Ongoing	Spring		Sand and gravel			EPA/LA
Tully (BH1)	09_019	Kildare	273313	210923	Jun-08	Ongoing	BH	Logger	Sand and gravel	9.00		EPA/LA
Borrismore Creek	10_005 (Kny 12/8)	Kilkenny	233000	161500	Apr-75	Ongoing	BH	Chart recorder to Oct-07, then logger	Dinantian karstified limestone	36.00	147.34	GSI/OPW
Freshford to Johnstown Rd BH	10_009	Kilkenny	231261	167072	Oct-07	Ongoing	BH	Logger	Dinantian pure bedded limestone	13.50		EPA/LA
Laffansbridge	22_005	Tipperary	219100	146620	Oct-07	Ongoing	BH	Logger	Dinantian pure bedded limestone	10.00		EPA/LA
Mayglass	26_008	Wexford	300134	112570	Mar-08	Ongoing	BH	Logger	Dinantian pure bedded limestone	60.00		EPA/LA
San Antone House (B&B)	26_011	Wexford	305307	114357	Mar-09	Ongoing	BH	Logger	Dinantian pure bedded limestone	100.00		EPA/LA
Vickerstown	11_014	Laois	261234	200342	Jan-08	Ongoing	BH	Logger	Dinantian pure bedded limestone	25.00		EPA/LA
Paulstown	10_014	Kilkenny	266048	157294	No data	No data	Spring		Dinantian pure bedded limestone			EPA/LA
Rathduff	10_017 (Kny 27/58)	Kilkenny	250500	143300	Aug-81	Ongoing	BH	Chart recorder to Mar-08, then logger	Dinantian dolomitised limestone	62.00	46.75	GSI/OPW
Pub in Pike	10_016	Kilkenny	254859	156017	Oct-07	Ongoing	BH	Logger	Dinantian upper impure limestone	20.00		EPA/LA
Kilmaganny	10_011	Kilkenny	245805	137446	May-08	Ongoing	BH	Logger	Dinantian lower impure limestone	15.00		EPA/LA
Knocktopher	10_012 (Kny 31/72)	Kilkenny	253140	135930	Aug-80	Ongoing	BH	Chart recorder to May-08, then logger	Kiltorcan Sandstone	40.00	61.67	GSI/OPW
Adamstown (BH2 – Deer Farm)	26_001	Wexford	285900	126000	Mar-08	Ongoing	BH	Logger	Ordovician Volcanics	44.00		EPA/LA
Slieveroe (BH1)	10_018	Kilkenny	263315	113960	Mar-08	Ongoing	BH	Logger	Ordovician Volcanics	100.00		EPA/LA
Bord na Móna – Allen	09_003	Kildare	280086	220996	No data	No data	BH	Logger				EPA/LA
Duffy's Crossroads	09_007	Kildare	266614	238096	Jun-08	Ongoing	BH	Logger				EPA/LA

PF, Pollardstown Fen; BH, borehole; GSI, Geological Survey of Ireland; OPW, Office of Public Works; LA, local authority; mbgl, metres below ground level; maOD, metres above Ordnance Datum.

From Tedd *et al.*, 2011.

¹After Daly (1994).
²After Daly (1982).
³Derived from pumping tests on wells that are mainly partially penetrating.
⁴Tests are not practical where the yield is less than 10 m³/day.
⁵An average value over the productive section of pumped wells.
⁶Obtained from pumping tests, core measurement or hydrograph analysis.
⁷Boreholes failing to provide a minimum domestic supply (10 m³/day) are not uncommon in these formations.

APPENDIX 3 – additional hydrogeological maps and catchment areas for each of the 8 monitoring points studied.

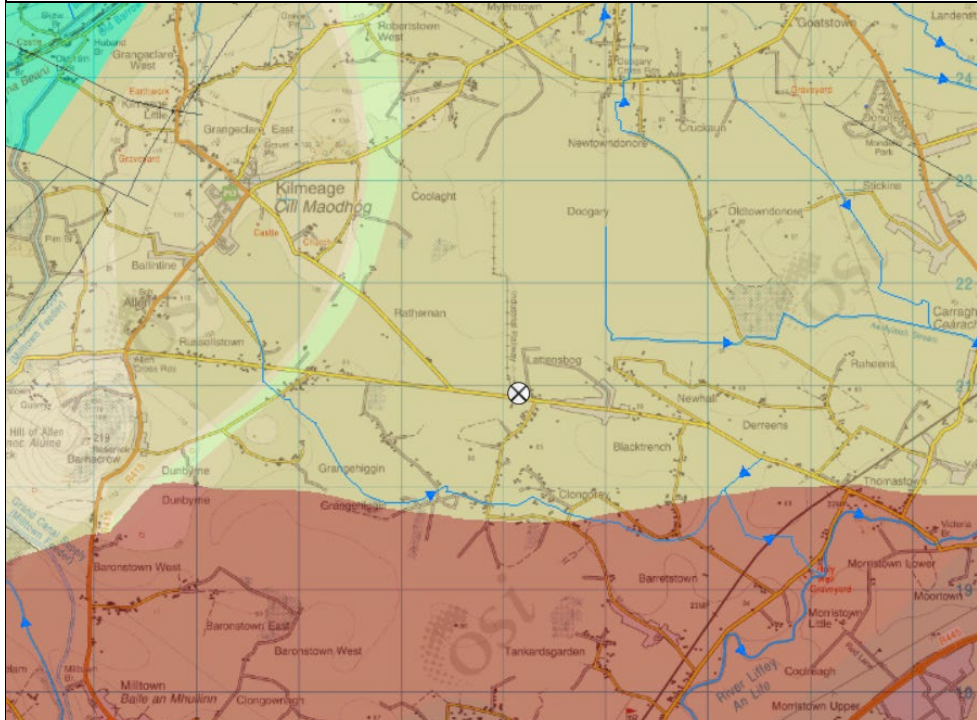
Aquifer map legend

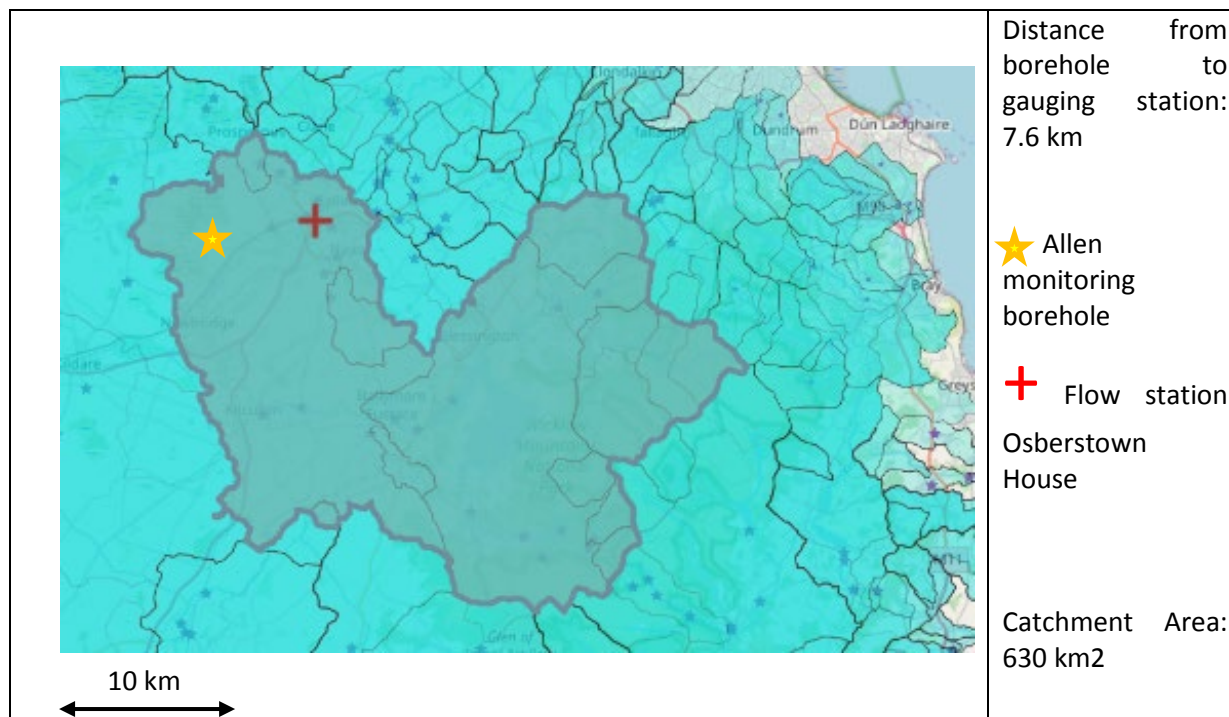
Gravel Aquifer

-  Locally important gravel aquifer
-  Regionally important gravel aquifer

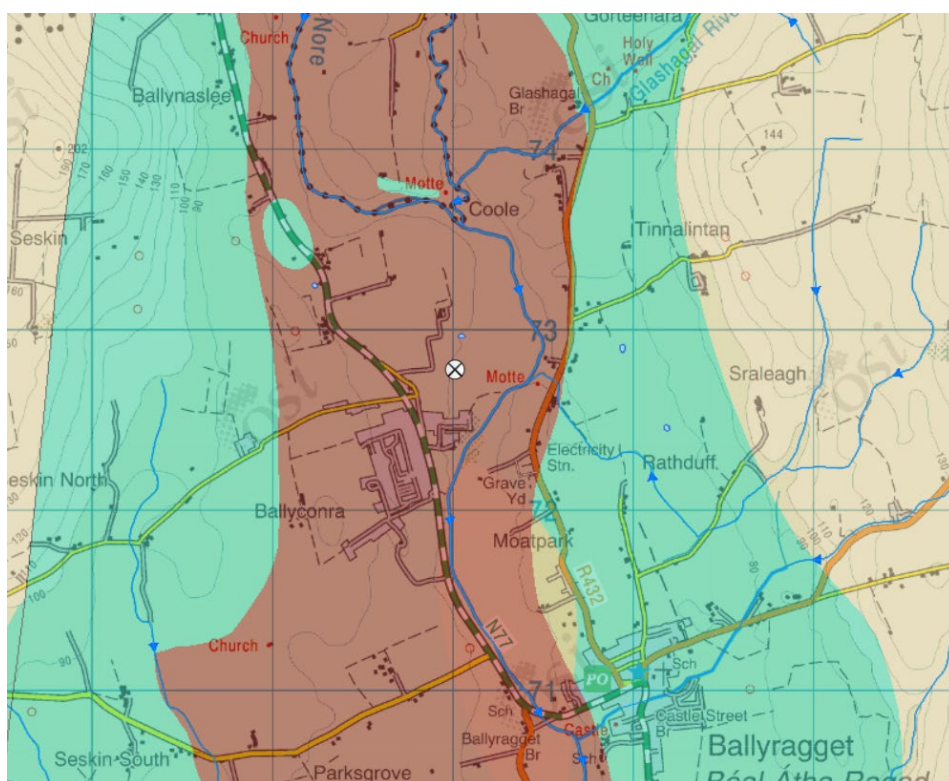
Bedrock Aquifer

-  Rkc - Regionally Important Aquifer - Karstified (conduit)
-  Rkd - Regionally Important Aquifer - Karstified (diffuse)
-  RK - Regionally Important Aquifer - Karstified
-  Rf - Regionally Important Aquifer - Fissured bedrock
-  Lm - Locally Important Aquifer - Bedrock which is Generally Moderately Productive
-  Lk - Locally Important Aquifer - Karstified
-  LI - Locally Important Aquifer - Bedrock which is Moderately Productive only in Local Zones
-  PI - Poor Aquifer - Bedrock which is Generally Unproductive except for Local Zones
-  Pu - Poor Aquifer - Bedrock which is Generally Unproductive

Groundwater monitoring station name	Grid refs (Irish National Grid)
ALLEN (IE_EA_G_0008_1400_0003)	E 280087.00 , N 220935.00
Depth of borehole(m)	Elevation/dipping reference (mAOD, Malin)
37.4 m	86 mAOD
Subsoil thickness (m)	Groundwater level range (max/min) (m)
5-10 m (depth to top of aquifer, m below surface)	82.85 – 84.32 m
Record length (from/to)	
Jan 1997 – Jul 2020	
Surface water monitoring station	Grid refs (Irish National Grid)
Osberstown House	E 287669.00 , N 221566.00
Elevation (mAOD, Malin)	Flow range (max/min) (m3/s)
72.5 m	0.041 – 0.461 m3/s
Record length (from/to)	
May 2009 – Dec 2020	LIMESTONE KARST AQUIFER
	
Distance from borehole to river: 900 - 1200 m  Allen monitoring borehole  Surface water features	



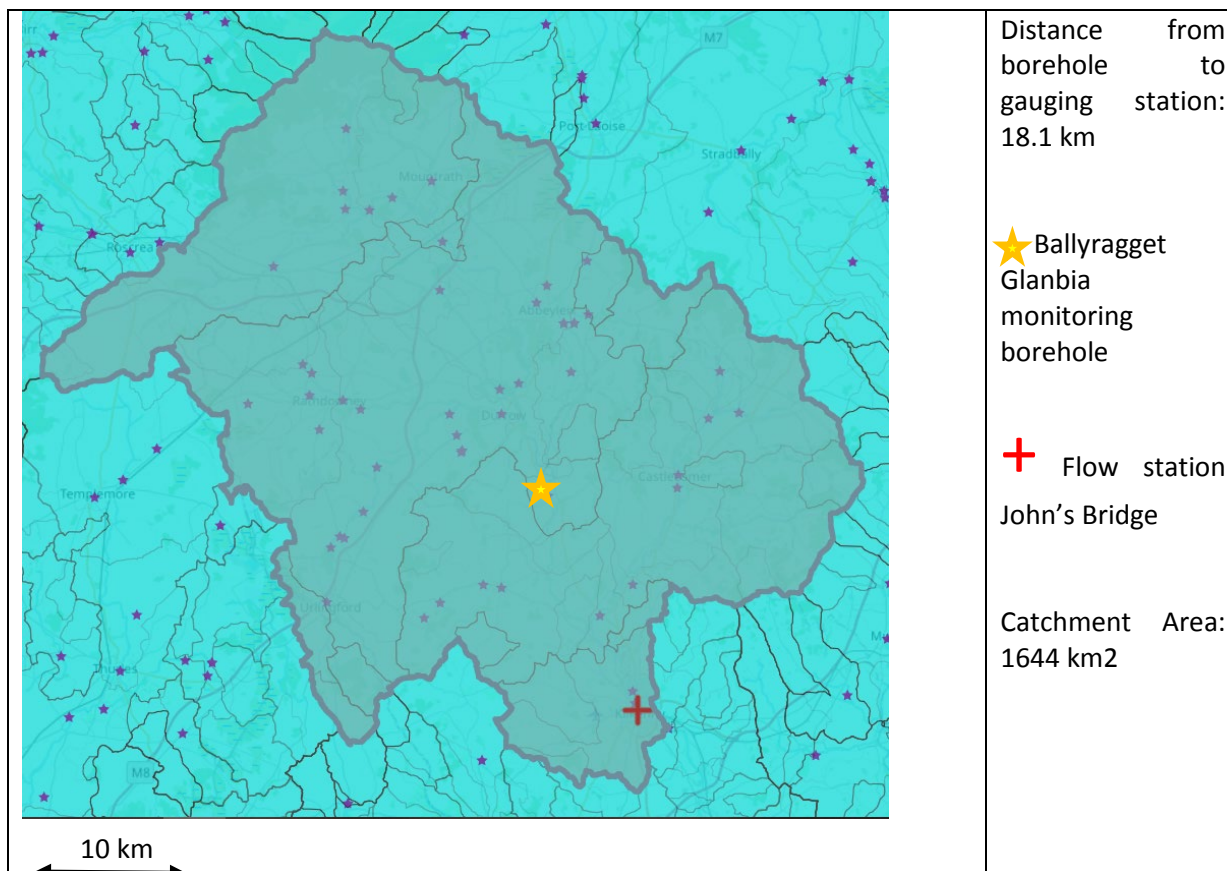
Groundwater monitoring station name	Grid refs (Irish National Grid)
BALLYRAGGET (IE_SE_G_0163_1500_0002)	GLANBIA E 244002.00 , N 172802.00
Depth of borehole(m)	Top borehole/dipping reference (mAOD, Malin)
18 m	67 mAOD Malin
Subsoil thickness (m)	Groundwater level range (max/min) (m)
5-12.2 m (depth to top of aquifer, m below surface)	64.819 m to 62.097 m
Record length (from/to)	
Mar 2008 – Oct 2020	
Surface water monitoring station	Grid refs (Irish National Grid)
John's Bridge (15002)	E 250777.00 , N 156020.00
Elevation (mAOD, Malin)	Flow range (max/min) (m3/s)
44.17 m	0.524 – 341.142 m3/s
Record length (from/to)	
Oct 1971 – Dec 2017	SAND & GRAVEL AQUIFER

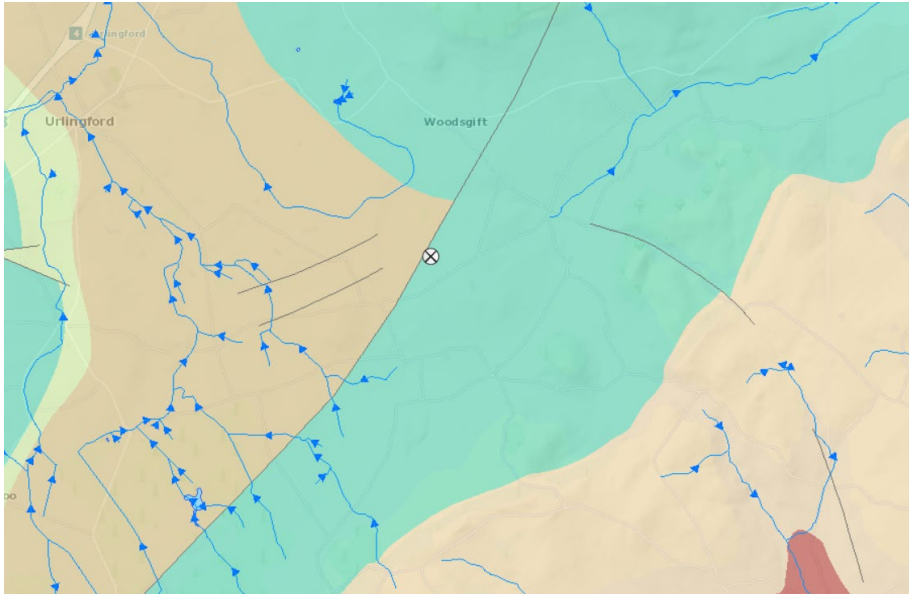


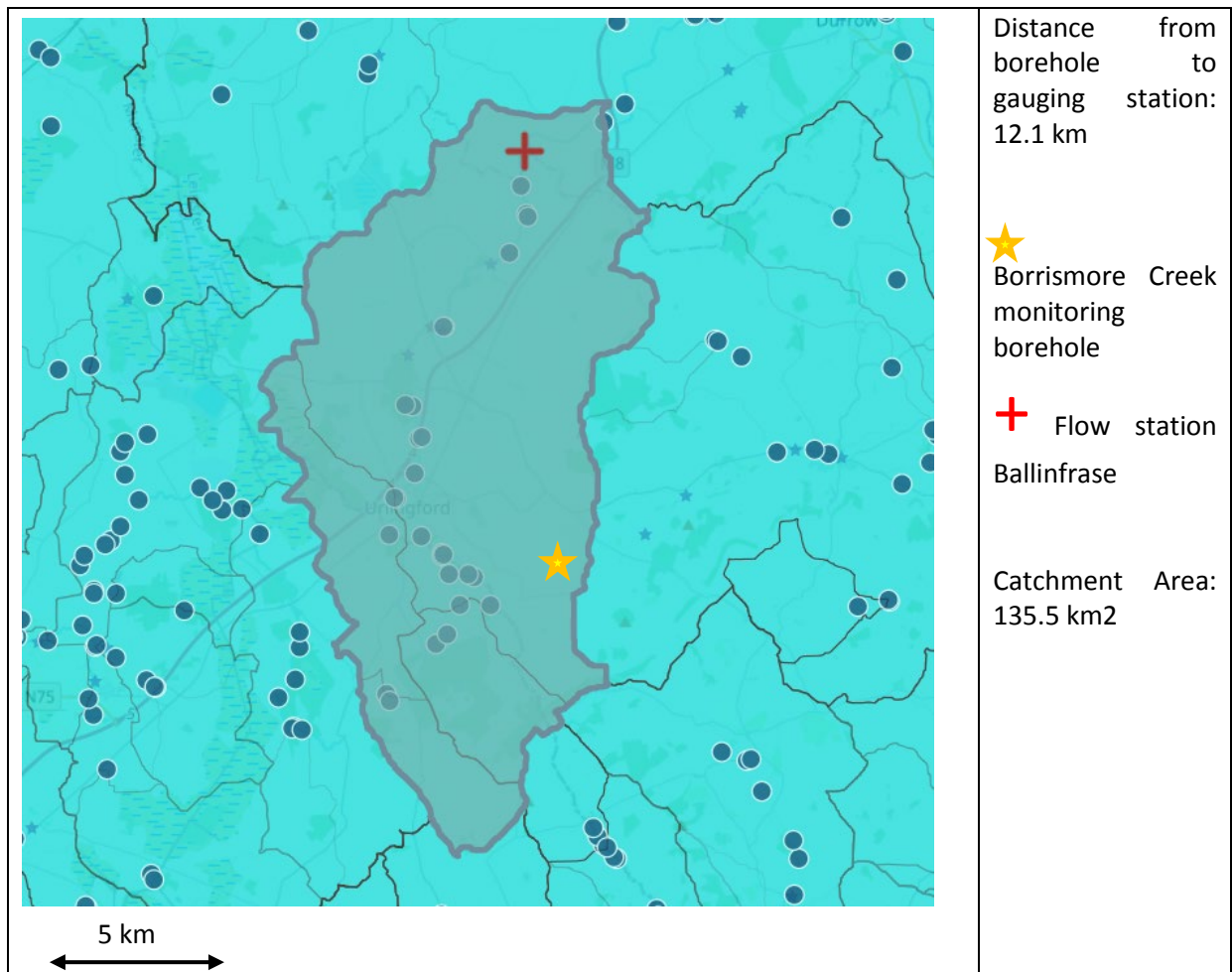
Distance from borehole to river: 250 - 450 m (River Nore)

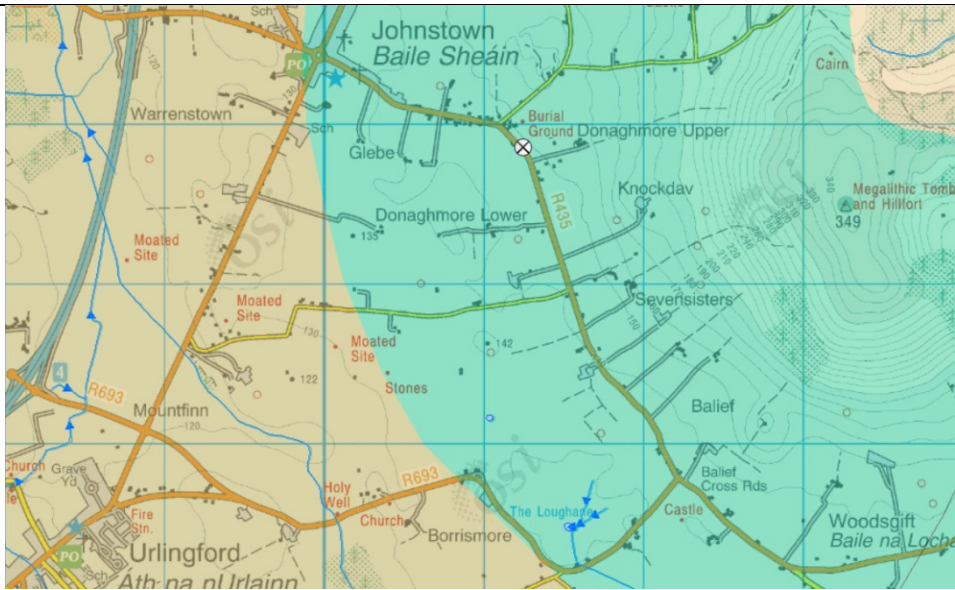
⊗ Ballyragget Glanbia monitoring borehole

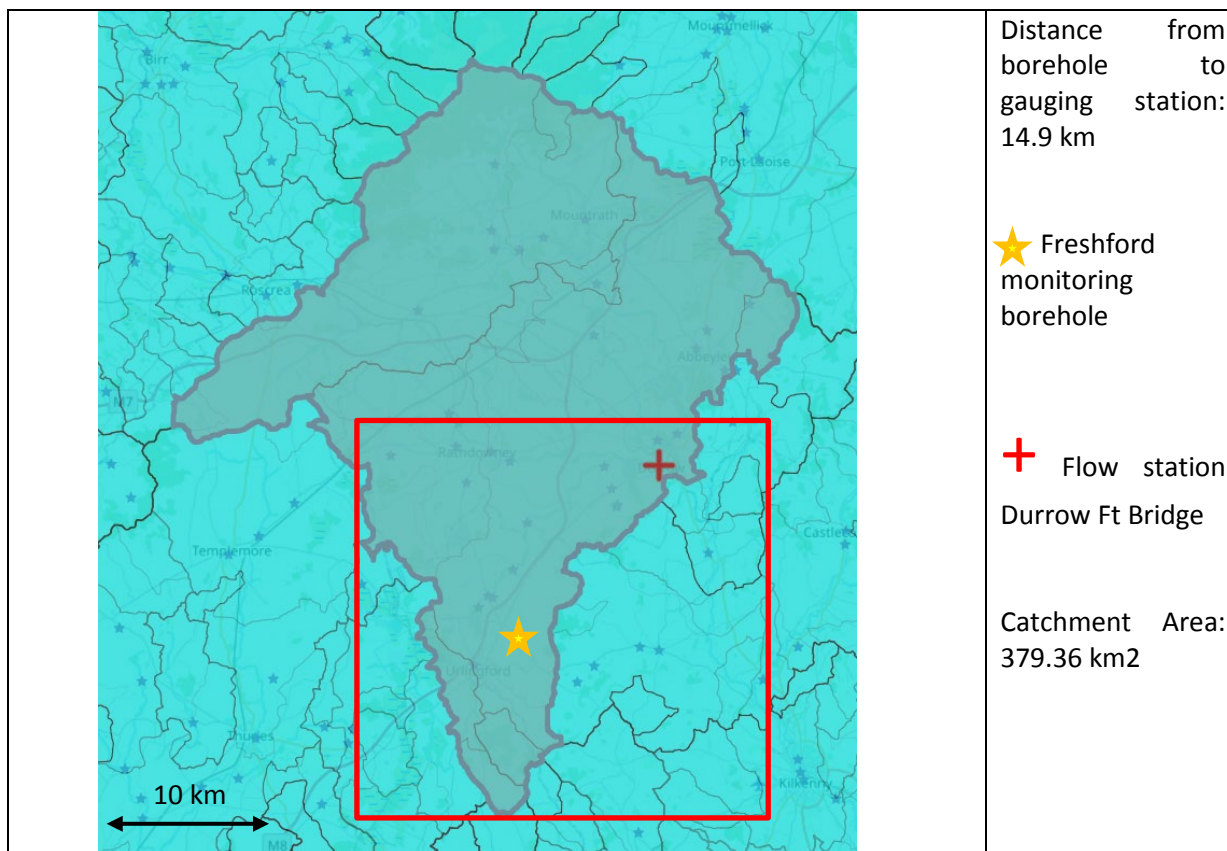
➔ Surface water features

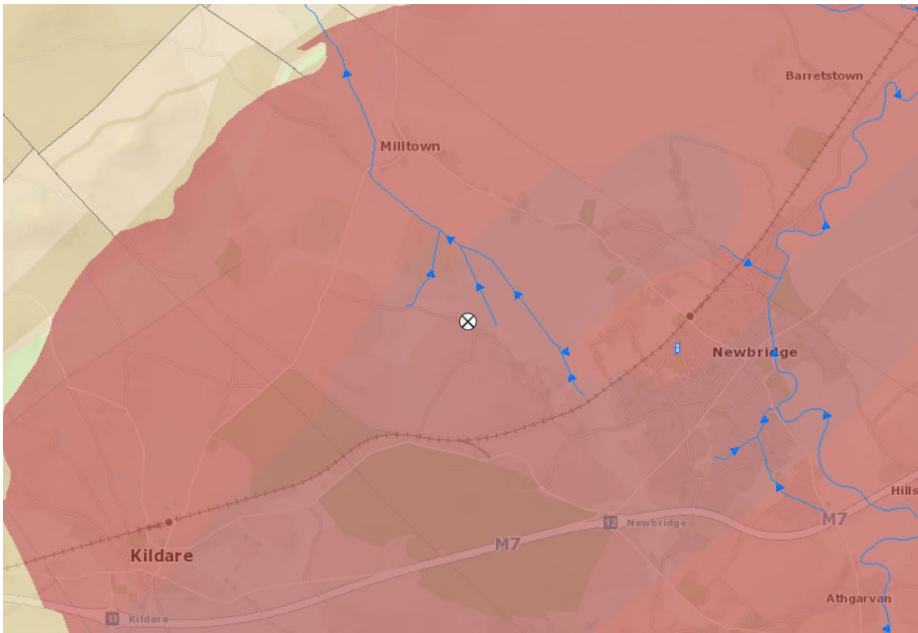


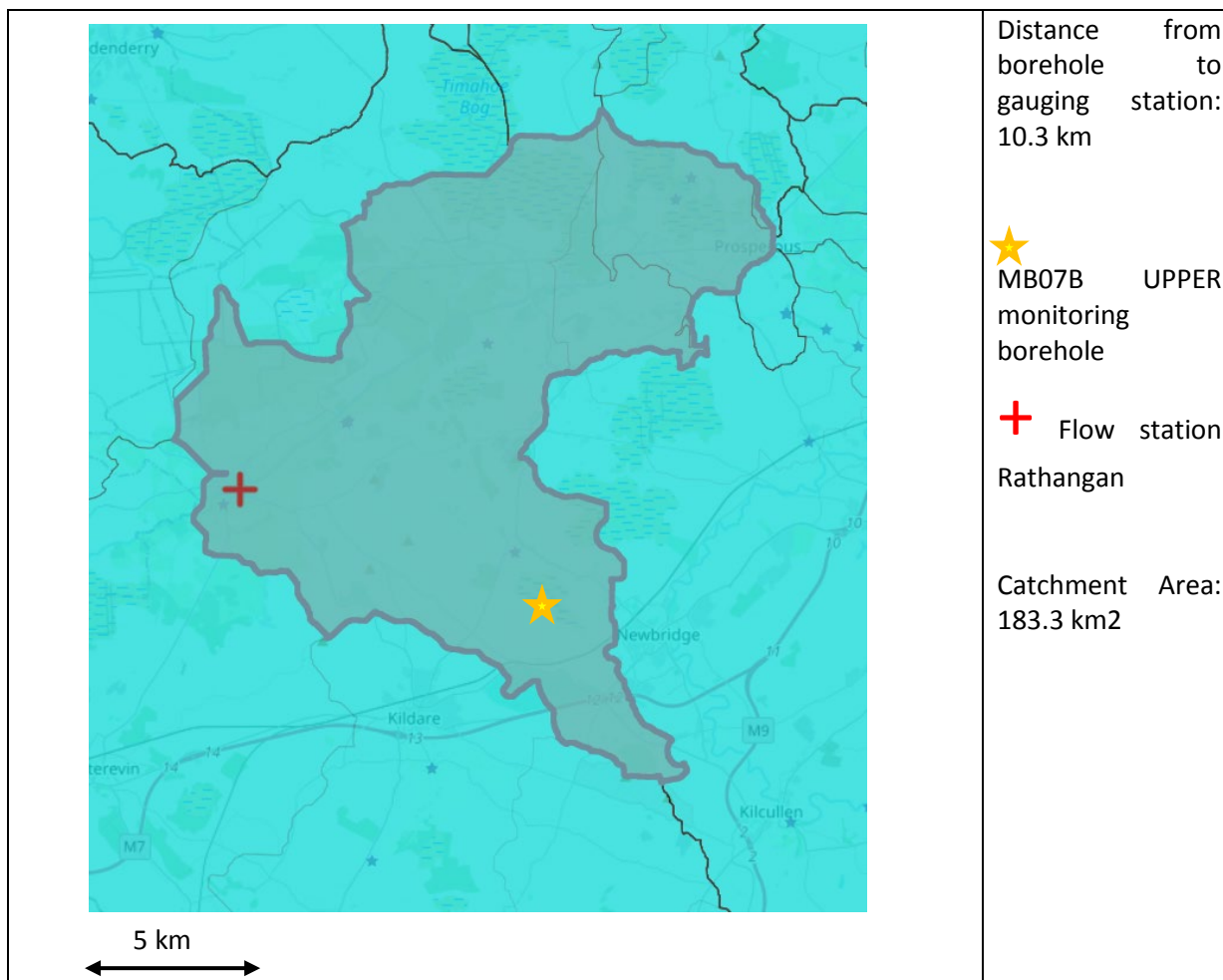
Groundwater monitoring station name		Grid refs (Irish National Grid)
BORRISMORE CREEK (IE_SE_G_0156_1500_0005)		E 233000.00 , N 161499.00
Depth of borehole(m)		Elevation/dipping reference (mAOD, Malin)
36 m		141 mAOD
Subsoil thickness (m)		Groundwater level range (max/min) (m)
6.1 m (depth to top of aquifer, m below surface)		128.22 – 140.04 m
Record length (from/to)		
Apr 1975 – Aug 2020		
Surface water monitoring station		Grid refs (Irish National Grid)
BALLINFRASE		E 231570.00 , N 173535.00
Elevation (mAOD, Malin)		Flow range (max/min) (m ³ /s)
102.237 m		0.214 – 22.4 m ³ /s
Record length (from/to)		
Jul 2001 – Mar 2021		KARST AQUIFER
 1 km		Distance from borehole to river: 1150 – 1350 m
		⊗ Borrismore Creek monitoring borehole → Surface water features

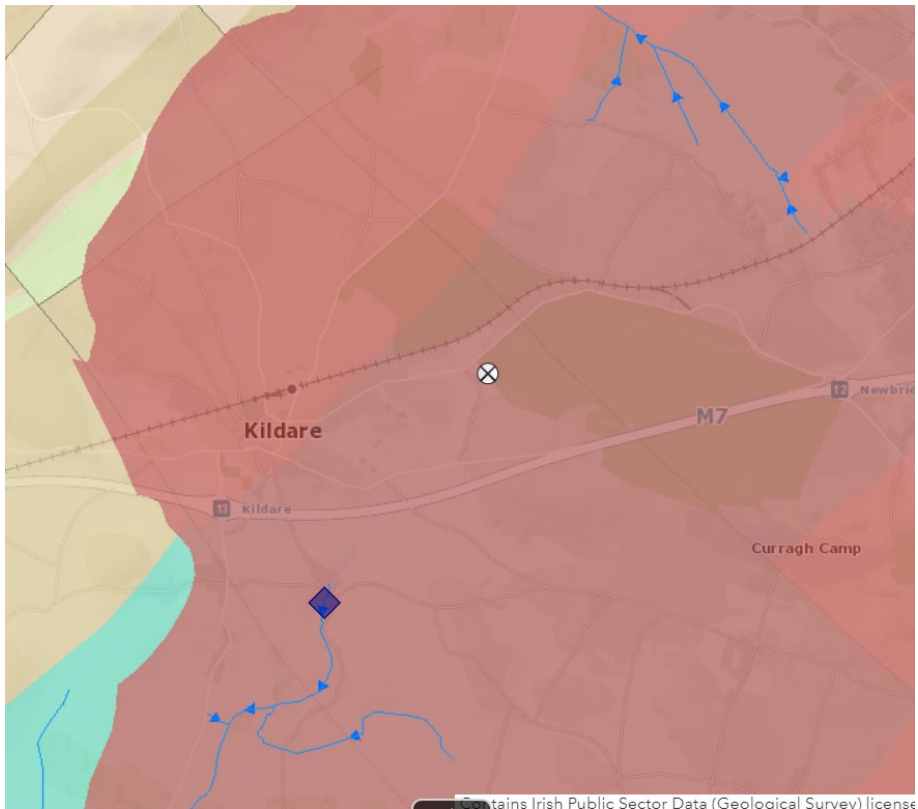


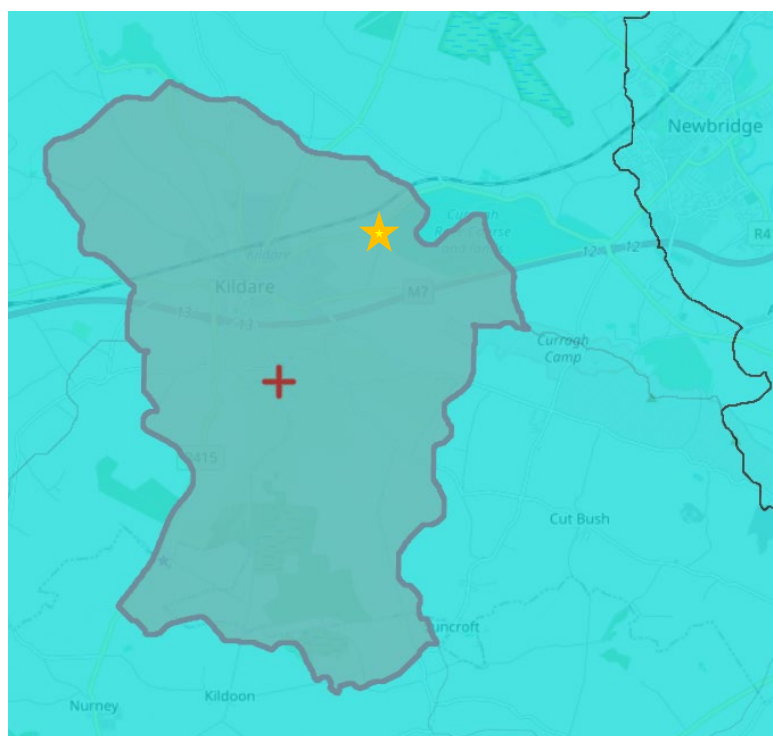
Groundwater monitoring station name			Grid refs (Irish National Grid)
FRESHFORD	–	JOHNSTOWN RD	E 231211.90 , N 165880.24
(IE_SE_G_0156_1500_0009)			
Depth of borehole(m)			Elevation/dipping reference (mAOD, Malin)
13.5 m (sump at 12.3 m)			151 mAOD Malin
Subsoil thickness (m)			Groundwater level range (max/min) (m)
13.7 m			143.09 m to 137.6 mAOD
Record length (from/to)			
Apr 2008 – Aug 2020			
Surface water monitoring station			Grid refs (Irish National Grid)
DURROW FR BRIDGE			E 240611.00 , N 177479.00
Elevation (mAOD, Malin)			Flow range (max/min) (m3/s)
83 mAOD			61.761 m3/s to 0.038 m3/s
Record length (from/to)			
Jan 1972 – Oct 2018			KARSTIC AQUIFER
			Distance from borehole to river: 2400 - 2600 m (River Goul)
			 Freshford monitoring borehole



Groundwater monitoring station name	Grid refs (Irish National Grid)
MB07B UPPER (IE_SE_G_0106_1400_0014)	E 276820.00 , N 215562.00
Depth of borehole(m)	Elevation/dipping reference (mAOD, Malin)
48.04 (depth of continuous borehole MB 07A Middle)	105 mAOD
Subsoil thickness (m)	Groundwater level range (max/min) (m)
3-5 m (depth to top of aquifer, m below surface)	85.92 – 87.33 m
Record length (from/to)	
May 2008 – Jul 2020	
Surface water monitoring station	Grid refs (Irish National Grid)
Rathangan	E 267336.00 , N 219356.00
Elevation (mAOD, Malin)	Flow range (max/min) (m3/s)
72 m	0.134 – 13.367 m3/s
Record length (from/to)	
Jan 1999 – Jun 2020	SAND & GRAVEL AQUIFER
 Distance from borehole to river: 250 – 450 m ⊗ MB07B UPPER monitoring borehole ➔ Surface water features	



Groundwater monitoring station name	Grid refs (Irish National Grid)
MB30 (IE_SE_G_0106_1400_0012)	E 275029.00 , N 213206.00
Depth of borehole(m)	Elevation/dipping reference (mAOD, Malin)
24 m	108 mAOD
Subsoil thickness (m)	Groundwater level range (max/min) (m)
3-5 m (depth to top of aquifer, m below surface)	87.89 – 90.92 m
Record length (from/to)	
Apr 2008 – Jul 2020	
Surface water monitoring station	Grid refs (Irish National Grid)
Japanese Gardens	E 273420.00 , N 210801.00
Elevation (mAOD, Malin)	Flow range (max/min) (m3/s)
87 m	0.025 – 0.461 m3/s
Record length (from/to)	
Jan 1982 – Sep 2020	SAND & GRAVEL AQUIFER
 Distance from borehole to river: 2800 – 3100 m ⊗ MB30 monitoring borehole → Surface water features ◆ Japanese Gardens flow station	



2 km

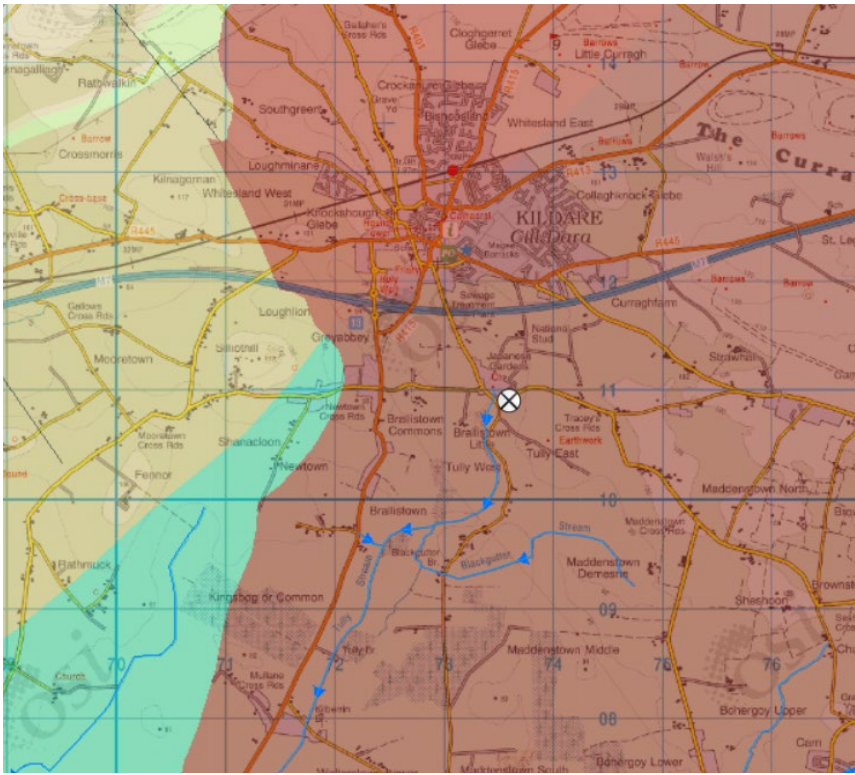
Distance from
borehole to
gauging station:
2.9 km

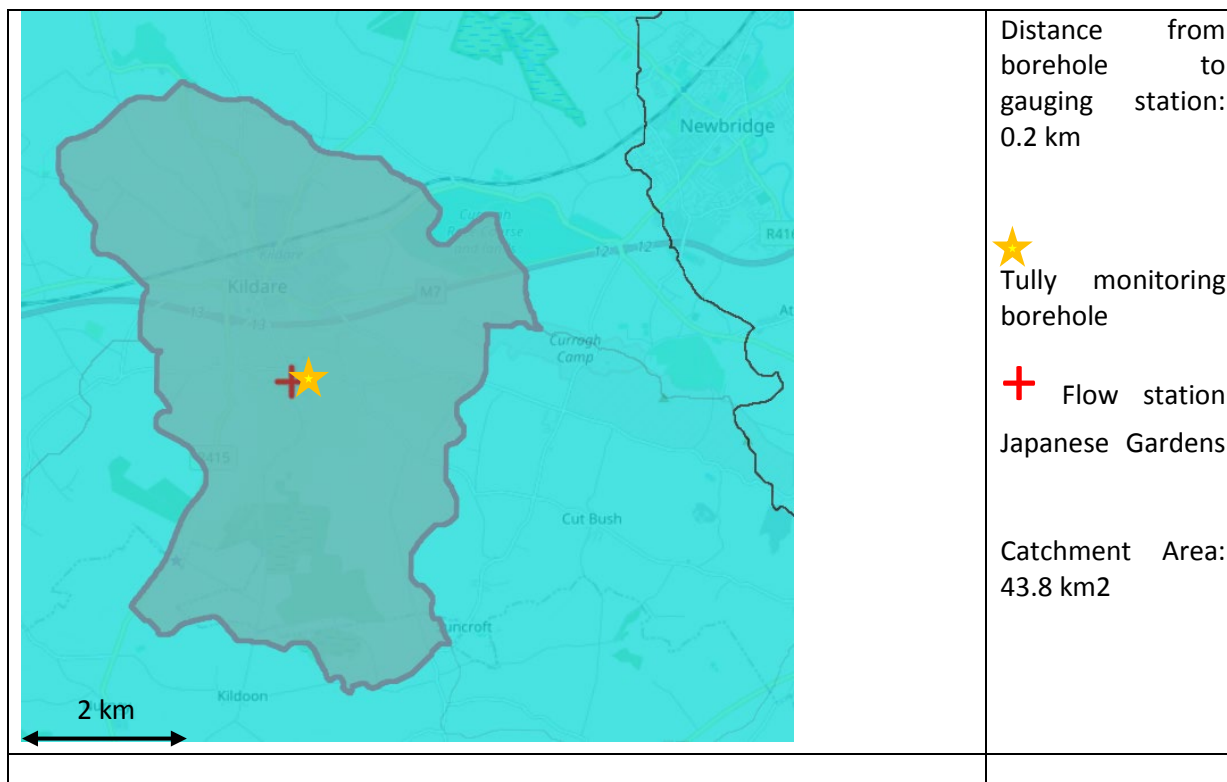
★
MB30 monitoring
borehole

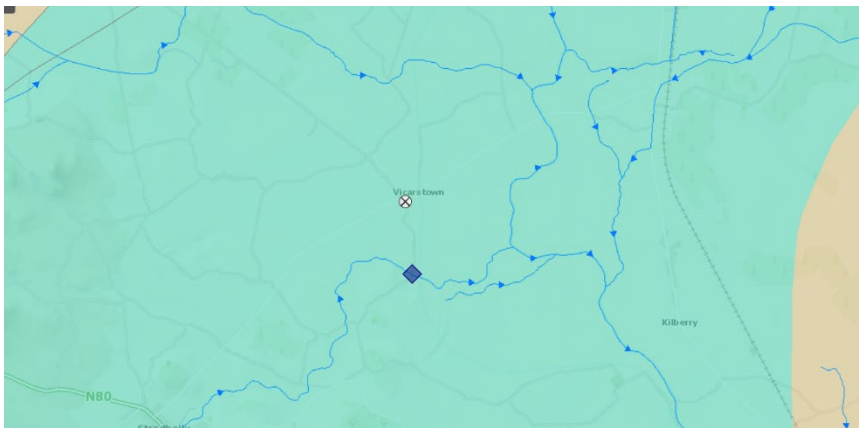
✚ Flow station
Japanese Gardens

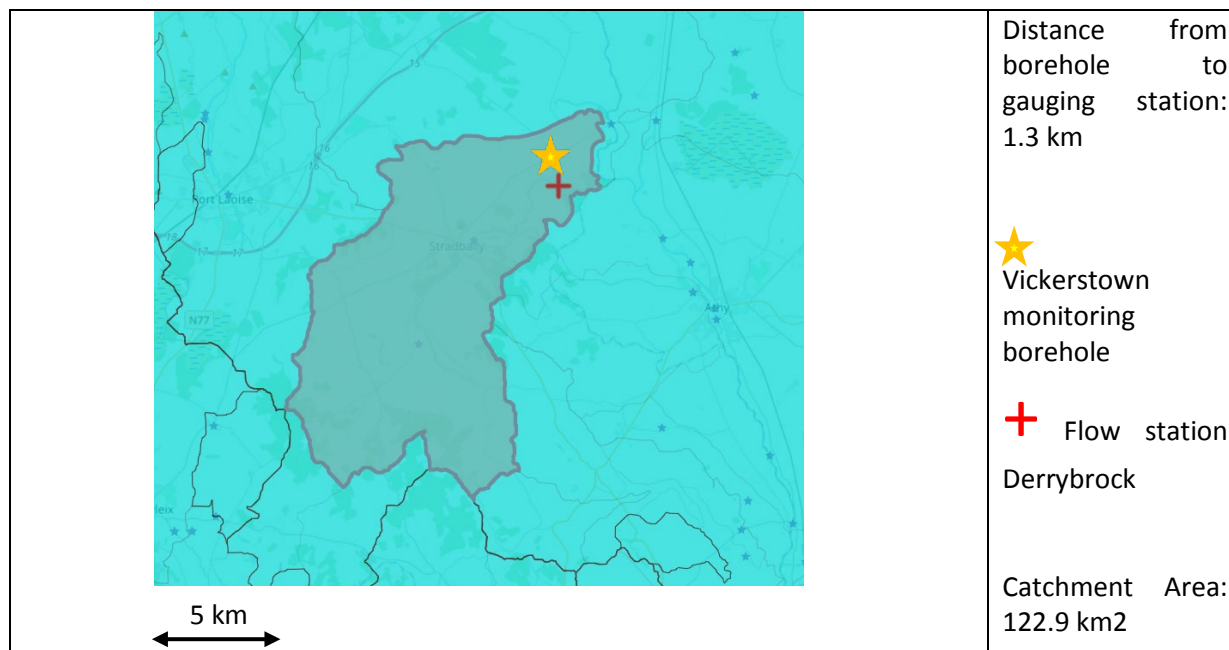
Catchment Area:
43.8 km²

Groundwater monitoring station name	Grid refs (Irish National Grid)
TULLY (IE_SE_G_0133_1400_0019)	E 273531.00 , N 210922.00
Depth of borehole(m)	Elevation/dipping reference (mAOD, Malin)
9 m	87 mAOD
Subsoil thickness (m)	Groundwater level range (max/min) (m)
3-5 m (depth to top of aquifer, m below surface)	84.67 – 85.52 m
Record length (from/to)	
Jan 2008 – Sep 2020	
Surface water monitoring station	Grid refs (Irish National Grid)
Japanese Gardens	E 273420.00 , N 210801.00
Elevation (mAOD, Malin)	Flow range (max/min) (m3/s)
87 m	0.025 – 0.461 m3/s
Record length (from/to)	
Jan 1982 – Sep 2020	SAND & GRAVEL AQUIFER

 1 km	Distance from borehole to river: 150 – 250 m ⊗ Tully monitoring borehole → Surface water features
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Groundwater monitoring station name	Grid refs (Irish National Grid)
VICKERSTOWN (IE_SE_G_0153_1600_0014)	E 261234.00 , N 200341.00
Depth of borehole(m)	Elevation/dipping reference (mAOD, Malin)
25 m	65 mAOD
Subsoil thickness (m)	Groundwater level range (max/min) (m)
13.7 m (depth to top of aquifer, m below surface)	58.50 – 62.55 m
Record length (from/to)	
Oct 1995 – Sep 2020	
Surface water monitoring station	Grid refs (Irish National Grid)
Derrybrock	E 261424.00 , N 199067.00
Elevation (mAOD, Malin)	Flow range (max/min) (m ³ /s)
58 m	0 – 16.917 m ³ /s
Record length (from/to)	
Feb 1980 – Oct 2020	KARST AQUIFER
 Distance from borehole to river: m ⊗ Vickerstown monitoring borehole → Surface water features ◆ Derrybrock flow station	



APPENDIX C – AquiMod methodology

AquiMod is a lumped parameter computer model that has been developed to simulate groundwater level time series at observational boreholes (Mackay et al., 2014a). It is based on hydrological algorithms that simulates the movement of groundwater within the soil zone, the unsaturated zone, and the saturated zone. The lumped models neglect complexities included in distributed groundwater models but maintains some of the fundamental physical principles that can be related to the conceptual understanding of the groundwater system (Mackay et al., 2014b).

While AquiMod was originally designed to capture the behaviour of a groundwater system through the analysis of groundwater level time series, it can produce the infiltration recharge values and groundwater discharges from the aquifer as a by-product. AquiMod is driven by complete time series of forcing data for either historical or predicted future conditions. Running AquiMod in predictive mode can be used to fill in gaps in historical groundwater level time series, or calculate future groundwater levels. In addition to groundwater levels, it also provides predictions of historical and future recharge values and groundwater discharges. In the current application we use calibrated AquiMod models to estimate the recharge values at selected boreholes.

AquiMod consists of three modules (Figure C1). The first is a soil water balance module that calculates the amount of water that infiltrates the soil as well as the soil storage. The second module controls the movement of water in the unsaturated zone, mainly it delays the arrival of infiltrating water to the saturated zone. The third module calculates the variations in groundwater levels and discharges. The model executes the modules separately following the order listed above.

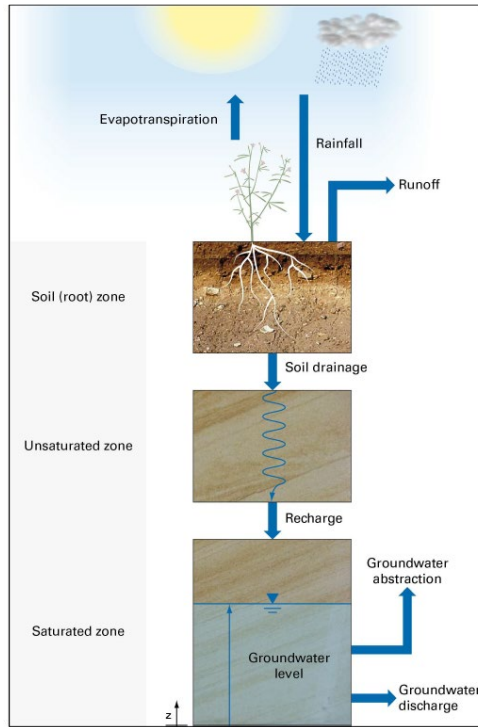


Figure C1 Generalised structure of AquMod (after Mackay et al., 2014a)

The soil moisture module

There are several methods available in AquMod that can be used to calculate the rainfall infiltration into the soil zone. In this study we use the FAO Drainage and Irrigation Paper 56 (FAO, 1988) approach. In this method, the capacity of the soil zone, from which plants draw water to evapotranspire, is calculated first using the plants and soil characteristics. Evapotranspiration is calculated according to the soil moisture deficit level compared to two parameters: Readily Available Water (RAW) and Total Available Water (TAW). These are a function of the root depth and the depletion factor of the plant in addition to the soil moisture content at field capacity and wilting point as shown in Equations C1 and C2.

$$TAW = Z_r(\theta_{fc} - \theta_{wp})$$

Equation C1

$$RAW = p \cdot TAW$$

Equation C2

Where Z_r [L] and p [-] are the root depth and depletion factor of a plant respectively, θ_{fc} [$L^3 L^{-3}$] and θ_{wp} [$L^3 L^{-3}$] are the moisture content at field capacity and wilting point respectively.

The FAO method is simplified by Griffiths et al. (2006) who developed a modified EA-FAO method. In this method the evapotranspiration rates are calculated as a function of the potential evaporation and an intermediate soil moisture deficit as:

$$\begin{aligned} e_s &= e_p \left[\frac{s_s^*}{TAW - RAW} \right]^{0.2} & s_s^* > RAW \\ e_s &= e_p & s_s^* \leq RAW \\ e_s &= 0 & s_s^* \geq TAW \end{aligned}$$

Equation C3



Where e_s [L] is the evpo-transpiration rate, e_p [L] is the potential evaporation rate and s_s^* [L] is the intermediate soil moisture deficit given by

$$s_s^* = s_s^{t-1} - r + e_p \quad \text{Equation C4}$$

Where r [L] is the rainfall at the current time step and s_s^{t-1} [L] is the soil moisture deficit calculated at the previous time step.

The new soil moisture deficit is then calculated from:

$$s_s = s_s^{t-1} - r + e_s \quad \text{Equation C5}$$

Griffiths et al. (2006) proposed that the recharge and overland flow are only generated when the calculated soil moisture deficit becomes zero. The remaining volume of water, the excess water, is then split into recharge and overland flow using a runoff coefficient. In Aquimod a baseflow coefficient is used to reflect the fact that a groundwater discharge is calculated rather than overland water. In this application, the baseflow coefficient is one minus the runoff coefficient.

The unsaturated zone module

The Aquimod version used in this study to simulate the movement of groundwater flow within the unsaturated zone is based on a statistical approach rather than a process-based approach. This method distributes the amount of rainfall recharge over several time steps where the soil drainage for each time step is calculated using a two-parameter Weibull probability density function. The Weibull function can represent exponentially increasing, exponentially decreasing, and positively and negatively skewed distributions. This can be used to focus the soil drainage over earlier or later time steps or to spread it over a number of time steps after the infiltration occurs. The shape of the Weibull function is controlled by two parameters, k and λ as shown in Equation A6.

$$f(t, k, \lambda) = \begin{cases} \frac{k}{\lambda} \left(\frac{t}{\lambda}\right)^{k-1} e^{-(t/\lambda)^k} & t > 0 \\ 0 & t \leq 0 \end{cases} \quad \text{Equation C6}$$

Where k and λ are two parameters the values of which are calculated during the calibration of the model and t is the time step.

The saturated zone module

Aquimod considers the saturated zone as a rectangular block of porous medium with dimensions L and B as its length and width [L] respectively. This block is divided into a number of layers, each has a defined hydraulic conductivity value, a storage coefficient value, and a discharging feature. The number of layers define the structure of the saturated module used in the study.

The mass balance equation that gives the variation of hydraulic head with time is given by:

$$SLB \frac{dh}{dt} = RLB - Q - A \quad \text{Equation C7}$$

Where:



S is the storage coefficient of the porous medium [-]

h is the groundwater head [L]

t is the time [T]

R is the infiltration recharge [$L T^{-1}$]

Q is the discharge out of the aquifer [$L T^{-1}$]

A is the abstraction rate [$L T^{-1}$]

It must be noted that in a multi-layered groundwater system as shown in Figure C2, we calculate one groundwater head (h) for the whole system. The discharges (Q) from Outlet 1, 2, etc. are calculated using the Darcy law. The total discharges can be summarised using the following equation:

$$Q = \sum_{i=1}^m \frac{T_i B}{0.5 L} \Delta h_i \quad \text{Equation C8}$$

Where:

m is the number of layers in the groundwater system [-]

T_i is the transmissivity of the layer i [$L T^{-2}$]

Δh_i is the difference between the groundwater head h and z_i , the elevation of the base of layer i

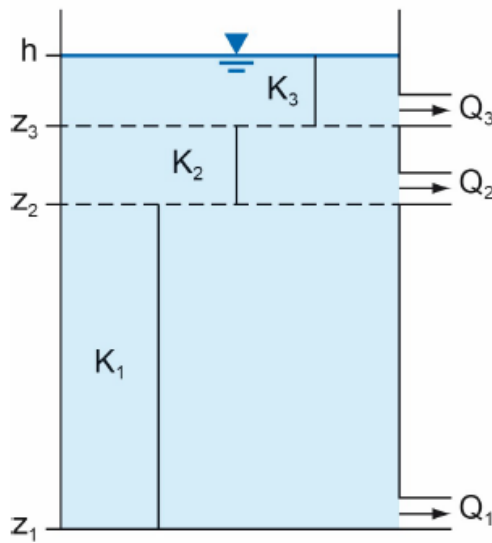


Figure C2 Representation of the saturated zone using a multi-layered groundwater system

Substituting Equation C8 into Equation C7 yields a numerical equation in the form:

$$S \frac{(h-h^*)}{\Delta t} = R - \sum_{i=1}^m \frac{T_i}{0.5 L^2} \Delta h_i - \frac{A}{LB} \quad \text{Equation A9}$$

Equation C9 is an explicit numerical equation that allows the calculation of the groundwater head h [L] at any time and using time steps of Δt [T]. In this equation h^* [L] is the groundwater head calculated at the previous time step and the term Δh_i [L] is calculated as $(h^* - z_i)$.



The terms S , T_i , and L are optimised during the calibration of the model. A groundwater system can be specified with one storage coefficient as shown in the equations above or with different storage coefficient values for the different layers. Several saturated modules are included in AquiMod to provide this flexibility and the model user can select the model structure that represent the conceptual understanding best.

Limitations of the model

AquiMod is a lumped groundwater model that aims at reproducing the behaviour of the observed groundwater levels. It tries to encapsulate the conceptual understanding of a groundwater system in a simple numerical representation. The model results have to be therefore discussed, taking this into consideration. For example, the model represents the groundwater system as a closed homogeneous medium, with no impact from any outer boundary or feature, whether physical or hydrological, such as the presence of rising and falling river stage.

Vertical heterogeneity can be accounted for by using multi-layered groundwater module structure. However, this model setting does not provide any information about the vertical connections between the layers as the discharge from all the layers is calculated using one representative groundwater head value. In other words, it is assumed that all layers are in perfect hydraulic connection.

As mentioned before, the model is designed to simulate the groundwater levels. However, it produces the recharge values and groundwater discharges as by products. In this application we use the calibrated model to calculate recharge. The mass balance equation (Equation C7) shows that recharge is a function of transmissivity and storage coefficient values, which are estimated during the calibration process of the model, i.e. they are not parameters with fixed values provided by the user. The inter-connections between these parameters leads to uncertainties in the estimated recharge values as a high storage coefficient value can produce a high recharge estimate and vice versa. To overcome this problem, it is suggested that the recharge values estimated by AquiMod are always presented as a range of possibilities rather than an absolute value. This can be achieved by estimating the recharge values from all the models that have a performance measure above than a threshold that is deemed acceptable by the user. The recharge estimates can then be presented as an average of all estimates and values corresponding to selected percentiles.

Model input and output

AquiMod includes a number of methods that calculates rainfall recharge as well as a number of model structure from which the user can select what better suits the case study.

Model input consists time series of forcing data including rainfall and potential evaporation, time series of anthropogenic impact mainly groundwater abstraction and time series of groundwater levels that will be used to calibrate the model. These time series must be complete, i.e. a value is available at every time step except the groundwater level time series, which can include missing data. The time step can be one day or multiple of days, and the model automatically calculate the size of the time step based on the input data time series.



The model is run first in calibration mode where a range of parameter values are specified for the different parameters included in the three model modules. A Monte Carlo approach is used to select the best parameter values. The performance of the model is measured by comparing the simulated groundwater levels to the observed ones using the Nash Sutcliff Efficient (NSE) or the Root Mean Squared Error (RMSE) performance measures. The parameter set that produces the best model performance is selected to run the model in evaluation mode.

When the model is run in evaluation mode, it produces output files that give recharge values, groundwater levels and groundwater discharges time series with time as specified in the input file. The number of output files is equal to the number of acceptable models set by the user.

APPENDIX D – Metran methodology

Metran applies transfer function noise modelling of (groundwater head) time series with usually daily precipitation and evaporation as input (Zaadnoordijk et al., 2019). The setup is shown in the Figure D1. If time series of other influences on the groundwater head are available, these contributions can be added to the deterministic part of the model. The stochastic part is the difference between the total deterministic part and the observations (the residuals). The corresponding input of the noise model should have the character of white noise.

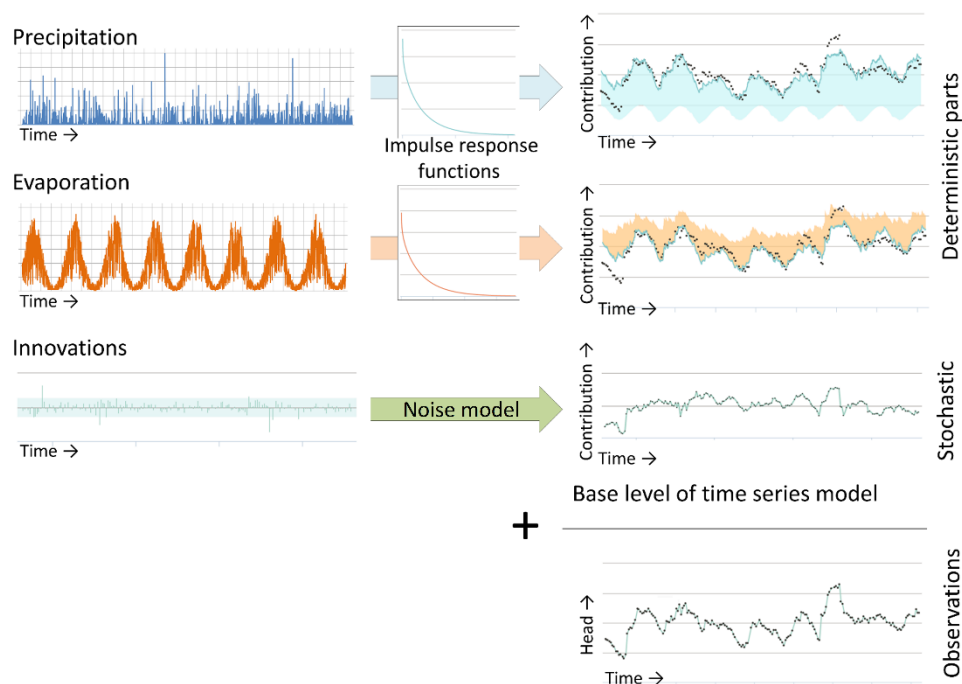


Figure D1 Illustration of METRAN setup

The stochastic part is needed because of the time correlation of the residuals, which does not allow a regular regression to obtain the parameter values of the transfer functions.

The incomplete gamma function is used as transfer function. This is a unimodal function with only three parameters that has a quite flexible shape and has some physical background (Besbes & de Marsily, 1984). The evaporation response is set equal to the precipitation response except for a factor (f_c). The noise model has one parameter that determines an exponential decay. Thus, for the standard setup with precipitation and evaporation, there are five parameters that have to be determined from the comparison with the observations. Three parameters regarding the precipitation response, the evaporation factor, and the noise model parameter (actually, the time series model has a fifth parameter, the base level, but this is



determined from the assumption that the average of the calculated heads is equal to the average of the observations). There are three extra parameters for each additional input series, such as pumping.

Limitations

Metran's time series model is linear. So, the model creation breaks down when the system is strongly nonlinear. This can occur e.g. when drainage occurs for high groundwater levels, when the ratio between the actual evapotranspiration and the inputted reference evaporation varies strongly, or when the groundwater system changed during the simulated period.

Metran is not able to find a decent time series model when the response function is not appropriate for the groundwater system. An example of this is a system with a separate fast and slow response as was found for a French piezometer in the Avre region, as is illustrated in Figure D2.

Finally, the parameter optimization of Metran uses a gradient search method in the parameter space, so it can be sensitive to initial parameter values in finding an optimal solution.

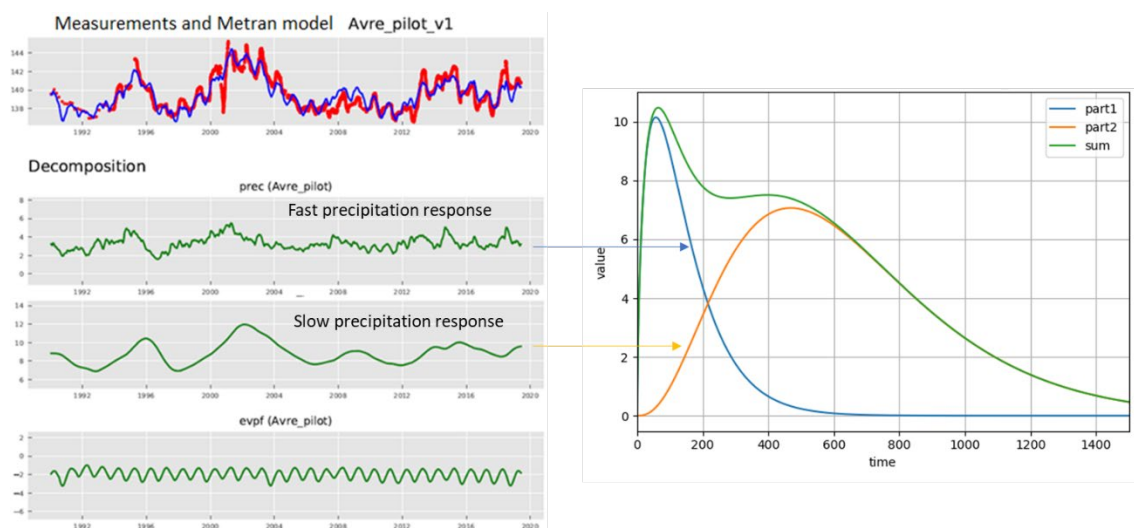


Figure D2. An example where the response function implemented in METRAN is not suitable for the groundwater system

Time step

Metran has been designed to work with explanatory series that have a daily time step. However, it has been adapted so that other time step lengths can be applied; although Metran still has the limitation that the explanatory variables have a constant frequency. For the TACTIC simulations of series with monthly or decadal meteorological input series, the time step has been set to 30 and 10 days, respectively. This time step has been applied from the end date backward.



Note that the heads may be irregular in time as long as the frequency is not greater than the frequency of the explanatory series.

Model output

The evaporation factor fc gives the importance of evapotranspiration compared to precipitation.

The parameter M_0 gives the total precipitation response, which is equal to the area below the impulse response function and the final value of the step response function.

The average response time is another characteristic of the precipitation response. The influence is illustrated in Figure D3 with the impulse response functions and head time series for two models with very different response times for time series of SGU in Sweden.

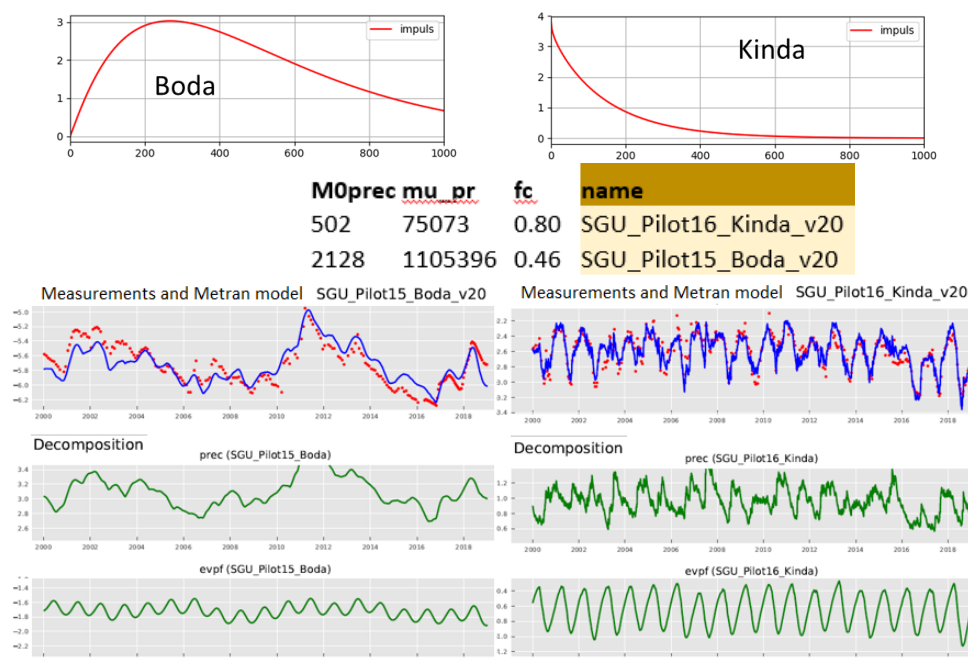


Figure D3 Illustration of Metran output for two case studies in Sweden with different response times.

Model quality

Metran judges a resulting time series model according to a number of criteria and summarizes the quality using two binary parameters Regimeok, Modok (see Zaadnoordijk et al., 2019):

- Regimeok = 1 : highest quality
- Modok = 1 (and Regimeok = 0) : ok
- Both zero = model quality insufficient



More detailed information on the model quality is given in the form of scores for two information criteria (AIC and BIC), a log likelihood, R², RMSE, and the standard deviations and correlations of the parameters.

Recharge

Although the transfer-noise modelling of Metran determines statistical relations between groundwater heads and explanatory variables, we like to think of the results in physical terms. It is tempting to interpret the evaporation factor, as the factor translating the reference into the actual evapotranspiration. Then, we can calculate a recharge as

$$R = P - fE \quad \text{Equation D1}$$

where R is recharge, P precipitation, E evapotranspiration, and f the evaporation factor.

Following the definitions used in the TACTIC project, this recharge R actually is the effective precipitation. It is equal to the potential recharge when the surface runoff is negligible. This in turn is equal to the actual recharge at the groundwater table if there also is no storage change or interflow. In such cases it may be expected that this formula indeed corresponds to the meteorological forcing of the groundwater head in a piezometer, so that it gives a reasonable estimate of the recharge. Obergfell et al. (2019) showed this for an area on an ice pushed ridge in the Netherlands. However, this assumes that all precipitation recharges the groundwater, which cannot be done in many places.

In Dutch polders with shallow water tables and intense drainage networks, it is reasonable to assume that the actual evapotranspiration is equal to the reference value. In that case, the factor f becomes larger than 1 because 1 mm of evaporation has less effect than 1 mm of precipitation (because part of the evaporation does not enter the ground but is immediately drained to the surface water system). In that case, we can calculate recharge as:

$$\begin{aligned} R &= P - fE & f &\leq 1 \\ R &= P/f - E & f &> 1 \end{aligned} \quad \text{Equation D2}$$

These simple formulas can be applied easily for the situations currently modelled in Metran and for the simulations that are driven by future climate data using the delta-change climate factors. However, it is noted that it is a crude estimate using assumptions that are easily violated. Because of this, the equations should be applied only to long term averages using only models of the highest quality.

APPENDIX E – Irish National Groundwater Recharge methodology

The groundwater recharge map shows estimated average annual recharge to the deep groundwater system. The ‘deep groundwater’ can be tapped steadily year-round and yields aren’t significantly influenced by seasonal changes. The recharge amount is shown in units of millimetres per year (mm/yr). The amount of recharge was calculated on daily timesteps over the period 1981-2010 and then averaged to give a yearly amount. The map has been updated as part of this project. The table below summarises the updates made to the Irish Groundwater Recharge map as part of this project (Hunter Williams et al, in press).

Table E.1: summary of main improvements in the Irish National Groundwater Recharge methodology and input data.

Dataset	2011 map	2020 map
Rainfall	30 year average annual rainfall 1971-2000. Data source Met Éireann.	MÉRA Daily rainfall in the period 1981-2010. Data source Met Éireann.
Actual Evapotranspiration	30 year average annual AE. Data source Met Éireann. One soil and reference crop type.	Daily AE in the period 1981-2010. Three soil drainage classes. One reference crop type. Data source Werner et al. (2019). Modified by GSI for areas underlain by peat (AE = ?? x PE)
Effective Rainfall	Average Annual Effective Rainfall = (30 year average annual Rainfall – 30 year average annual AE)	Average Annual Effective Rainfall = $\sum_{1981}^{2000} \frac{(\text{daily rainfall} - \text{daily AE})}{30 \text{ years}}$
Grid cell size	5 km x 5 km	2.5 km
Soil drainage	Teagasc soils map 1:40,000 (Fealy, 2007), re-categorised by GSI to Wet, Dry, Peat, Made	Teagasc soils map 1:40,000 (Fealy, 2007), re-categorised by GSI to Wet, Dry, Peat, Made Teagasc Indicative Soil Drainage map 1:250,000 (Creamer <i>et al.</i> , 2016), recategorised to well-drained, moderately-drained and poorly-drained soils Hybrid map created by mapping indicative soil drainage categories onto 1:40,000 soils map
Subsoil permeability and Groundwater vulnerability	GSI mapping available in 2011	GSI mapping available in 2020
Sand and gravel aquifers	GSI sand and gravel aquifer map (2008)	GSI sand and gravel aquifer map (2019)
Hydrogeological Scenarios	21 hydrogeological scenarios (excluding High-Low vulnerability areas)	24 hydrogeological scenarios (see table below. Better representation and improved recharge coefficients for peats; better representation of scree; additional scenarios for sand and gravel.

The main geological controls on groundwater recharge include soil drainage, subsoil type, subsoil permeability, subsoil thickness, and the ability of the underlying aquifer to accept percolating waters.

The amount of rain falling on the land minus how much of that rain is taken up by plants is also a factor that determines how much groundwater recharge there is at a particular location. This is known as the 'effective rainfall'.

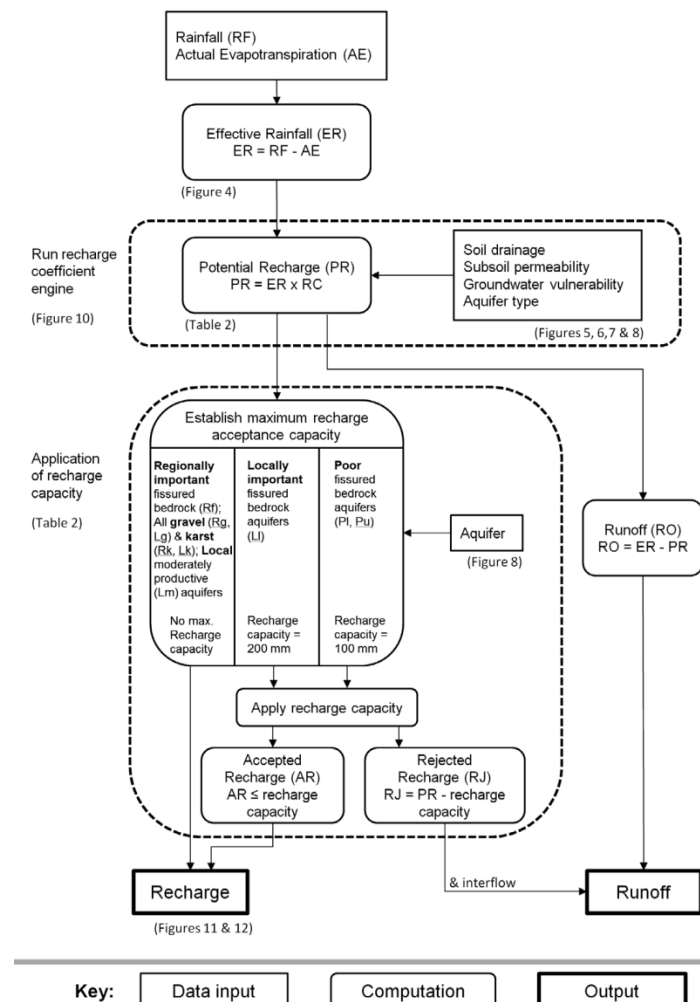
Different combinations of the geological factors give 24 hydrogeological scenarios. There is a 'recharge coefficient' for each scenario, which is the percentage of the 'effective rainfall' that may become groundwater recharge. The hydrogeological scenarios are summarised in Hunter Williams et al (in press) and are an update from Hunter Williams et al (2013). They are given in the Table below.

Table E.2: Hydrogeological scenarios and lower, mid and upper recharge coefficients (%)

Hydrogeological		Recharge coefficients (%)		
		Lower	Mid	Upper
1.i	E Vul: Areas where rock is at ground surface or karst feature	30	80-90	100
1.ii	E Vul: Sand & gravel overlain by well-drained soil	50	80-90	100
1.iii	E Vul: Sand & gravel overlain by poorly-drained (gley) soil	15	35-50	70
1.iv	E Vul: Till overlain by well-drained soil	45	50-70	80
1.v	E Vul: Till overlain by poorly-drained (gley) soil	5	15-30	50
1.vi	E Vul: Sand & gravel aquifer where the water table is $\leq$ 3m below surface and overlain by well-drained soil	50	80-90	100
1.vii	E Vul: Sand & gravel aquifer where the water table is $\leq$ 3m below surface and overlain by poorly-drained soil or peat	1	3-5	10
1.viii	E Vul: Blanket peat and Cut peat	1	15-30	50
1.ix	E Vul: Fen peat	1	3-5	10
2.i	H Vul: Sand & gravel aquifer, overlain by well-drained soil	50	80-90	100
2.ii	H Vul: High permeability subsoil (sand & gravel) overlain by well-drained soil	50	80-90	100
2.iii	H Vul: High permeability subsoil (sand & gravel) overlain by poorly-drained soil or peat	15	35-50	70
2.iv	H Vul: Sand & gravel aquifer, overlain by poorly-drained soil or peat	15	35-50	70
2.v	H Vul: Moderate permeability subsoil overlain by well-drained soil	35	50-70	80
2.vi	H Vul: Moderate permeability subsoil overlain by poorly-drained (gley) soil	10	15-30	50
2.vii	H Vul: Low permeability subsoil	1	20-30	40
2.viii	H Vul: Peat	1	5-15	20
2.ix	H Vul: Fen peat	1	3-5	10
3.i	M Vul: Moderate permeability subsoil overlain by well-drained soil	35	50-70	80
3.ii	M Vul: Moderate permeability subsoil overlain by poorly-drained (gley) soil	10	15-30	50
3.iii	M Vul: Low permeability subsoil	1	10-20	30
3.iv	M Vul: Peat	1	3-5	10
4.i	L Vul: Low permeability subsoil	1	5-10	20
4.ii	L Vul: Basin peat	1	3-5	10



The recharge coefficient polygons multiply agri-meteorological input data on a 2.5 x 2.5 km grid. The agri-meteorological data are produced by the Irish Centre for High-End Computing (ICHEC) from downscaled numerical weather prediction (NWP) models. The NWP models analysed in Werner et al. (2019) downscaled the European Centre for Medium-Range Weather Forecasts (ECMWF) ERAInterim global reanalyses dataset, and required significant computational hours on Ireland's national supercomputer to produce variables such as temperature, humidity, solar radiation wind-speed, etc. Two datasets (WRF v3.7.1, COSMO-CLM5) were downscaled by Dr. Paul Nolan (ICHEC) (Flanagan et al. 2019), and the third (MÉRA) was produced by Met Éireann. The FAO Penman Monteith Method was applied to dataset variables to produce reference evapotranspiration (ET_0), and the Soil Moisture Deficit Model (Schulte et al. 2005) was used to produce ET_a , SMD and ER variables used for this study. From the validations performed by Werner et al. 2019, the MÉRA dataset was chosen as having the highest overall skill. The figure below shows the process.



Indicative structure and method of GIS-based tool for estimating recharge
(from Hunter Williams et al 2013)

