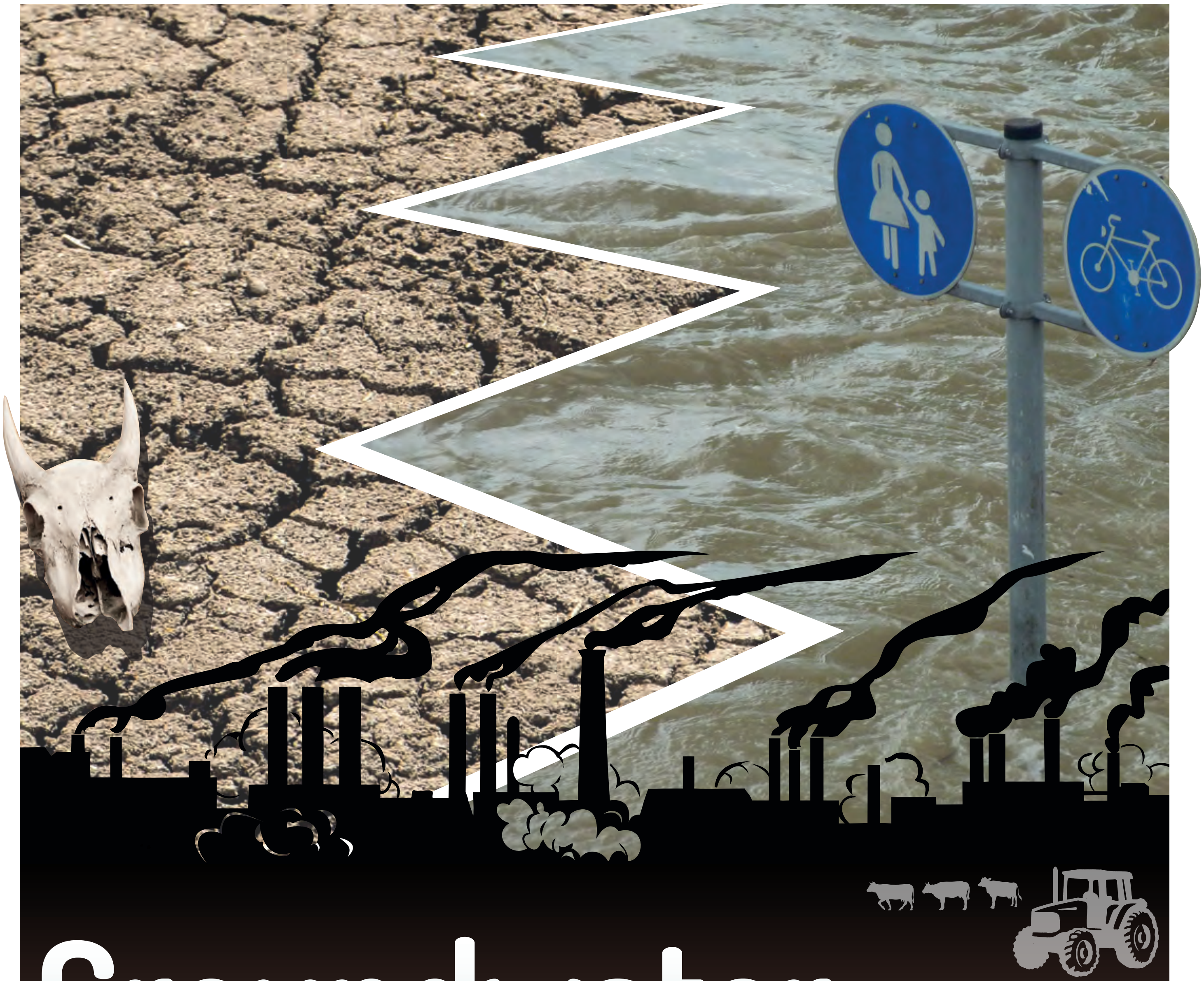

Groundwater

Drought, Floods & Climate Change

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS – Irish Group
Proceedings of the 39th Annual Groundwater Conference
Tullamore, Co. Offaly
30th April – 1st May 2019

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
(IRISH GROUP)

Presents

Groundwater: droughts, floods and climate change

Proceedings of the 39th Annual Groundwater Conference

Tullamore Court Hotel
Tullamore
Co. Offaly

30th April to 1st May, 2019

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS (IRISH GROUP)

Introduction

Founded in January 1976, the IAH-Irish Group has grown from 10 members to over 150 in 2018 and draws individuals from professional backgrounds ranging from academic to state agencies to private consultancies. The IAH committee consists of: President, Secretary, Treasurer, Burdon Secretary, Northern Region Secretary, Fieldtrip Secretary, Education & Publicity Secretary, Conference Secretary, plus a conference sub-committee.

Regular activities of the Irish Group include our annual two-day conference (currently held in Tullamore), an annual weekend fieldtrip, and a series of monthly lectures and technical meetings. Funding for the association is derived from membership fees and the annual conference. We welcome the participation of non-members in all our activities. Other activities of the IAH (Irish Group) include submissions to the Irish Government on groundwater, the environment and matters of concern to members, organising the cataloguing of the Burdon library and papers which are now housed in the Geological Survey of Ireland Library, the invitation of a guest expert speaker to give the David Burdon Memorial Lecture on a topic of current interest in the field, and informing the broader research community by contributing to the Geological Survey of Ireland's Groundwater Newsletter.

The Irish Group also provides bursaries to students undertaking postgraduate degrees in hydrogeology and pays the annual subscriptions of a few members in other countries as part of the IAH's Sponsored Membership Scheme. If you would like to apply for a student bursary, details can be found on the IAH (Irish Group) website shown below. IAH are encouraging members to highlight their local IAH Group to their colleagues/ students and to invite anyone they feel may be interested to join.

The IAH (Irish Group) is also a sponsoring body of the Institute of Geologists of Ireland (IGI).

For more information please refer to:	www.iah-ireland.org
Future events:	www.iah-ireland.org/upcoming-events/
IAH Membership (new or renewal):	www.iah.org/join_iah.asp
	www.iah.org/payonline

Selection of photographs from recent IAH Irish Group Fieldtrips


McCAFFREY COACH

2019 IAH (Irish Group) Conference "**Groundwater: drought, floods and climate change"**

In a report on the state of knowledge on climate change impacts for Ireland and under the heading "Water Management and Resources", (Desmond *et al*. 2017) state the following: "*There is a general lack of knowledge on the vulnerability of national water resources and infrastructure to a changing climate. This multi-faceted problem must be able to account for high and low flows, an ageing water infrastructure and increased demand due to population increases*." Under Recommendations, they state "*Adaptation actions will be required to avoid the adverse impacts of climate change and take advantage of any opportunities that may arise. In order to facilitate this process, an adaptation framework is needed. This would aim to advance work within and across sectors at a number of levels, through advancing the knowledge base, building capacity, communication of scientific knowledge and the implementation of actions. This adaptation framework would enable synergies between groups, generate understanding and learning (especially in relation to cross-cutting issues) and avoid duplication of efforts. The framework would encompass:*

- *advancement of the knowledge base and capacity building;*
- *development of sectoral risk and vulnerability assessment;*
- *development and assessment of adaptation options (including costs and benefits);*
- *development and implementation of effective governance structures."*

These quotes set the scene for our Conference. As speakers and conference papers demonstrate, even though groundwater and associated ecosystems are under threat from our climate crisis, groundwater is also part of the solution. Therefore, Irish hydrogeologists, with assistance and advice from our colleagues in Britain, have an important role in both the mitigation and adaptation areas; let us not only keep thinking and learning, but also contributing for the benefit of Irish society.

Reference
Desmond, M, O'Brien, P. and McGovern, F. 2017. A Summary of the State of Knowledge on Climate Change Impacts for Ireland. Report No. 223. Environmental Protection Agency. Available at: www.bit.ly/eparesearch223

I have given below a number of links to documents that may be relevant to Conference attendees as I feel that it is important that, while we should concentrate on groundwater issues, we need to understand, take account of and contribute to the national context.

Report of the Joint Committee on Climate Action Climate Change: A Cross-Party Consensus for Action. Houses of the Oireachtas. 2019.
https://data.oireachtas.ie/ie/oireachtas/committee/dail/32/joint_committee_on_climate_action/reports/2019/2019-03-28_report-climate-change-a-cross-party-consensus-for-action_en.pdf

National Adaptation Framework Planning for a Climate Resilient Ireland. Department of Communications, Climate Action and Environment. 2018.
https://www.dccae.gov.ie/documents/National%20Adaptation%20Framework.pdf

An Analysis of Abatement Potential of Greenhouse Gas Emissions in Irish Agriculture 2021-2030. Prepared by the Teagasc Greenhouse Gas Working Group Gary J. Lanigan & Trevor Donnellan (eds.). 2018.
https://www.teagasc.ie/media/website/publications/2018/An-Analysis-of-Abatement-Potential-of-Greenhouse-Gas-Emissions-in-Irish-Agriculture-2021-2030.pdf

Future Scenarios for Irish Agriculture: Implications for Greenhouse Gas and Ammonia Emissions. Trevor Donnellan, Kevin Hanrahan and Gary Lanigan. Teagasc 2018.
https://www.teagasc.ie/media/website/publications/2018/GHGscenarios2030final.pdf

Climate Change and Sustainability in the Agriculture and Food Sectors. Report of the Joint Committee on Agriculture, Food and the Marine.
https://data.oireachtas.ie/ie/oireachtas/committee/dail/32/joint_committee_on_agriculture_food_and_the_marine/reports/2018/2018-07-12_climate-change-and-sustainability-in-the-agriculture-and-food-sectors_en.pdf

We welcome all our speakers. We appreciate the effort taken in not only coming to the Conference to present, but also in writing a paper for the Conference Proceedings. Our colleagues from 'across the water' and from Texas are particularly welcomed; this interaction is very important for us in Ireland. We thank our exhibitors and sponsors. And, of course, we welcome all our attendees; may we enjoy the Conference and continue to work together to contribute to a climate proofed Ireland.

Donal Daly
President, IAH (Irish Group)

2019 IAH (Irish Group) Committee:

2019 Conference Sub-Committee:

2019 Education and Publicity Sub-Committee:

For more information and contact details please refer to: *www.iah-ireland.org*

Cover design: Two Plus George Ltd.

The proceedings for the 39th Annual Groundwater Conference 2019 will also be made available digitally on the IAH-Irish Group website within the next six months.

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The IAH (Irish Group) would also like to acknowledge the support of the following members and organisations whose staff have worked on the committee of the IAH-Irish Group throughout the year and helped to organise the conference:

Donal Daly

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An Roinn Cultúir, Oidhreachta agus Gaeltachta
Department of Culture, Heritage and the Gaeltacht

‘Groundwater: droughts, floods and climate change’

International Association of Hydrogeologists – Irish Group
Tullamore Court Hotel, Tullamore, Co. Offaly
Tuesday 30th April – Wednesday 1st May 2019

Programme Day 1, Tuesday 30th April

08:30 - 09:30 *Conference Registration; Tea, Coffee, & Exhibits*

INTRODUCTION

09:30 Welcome - Donal Daly – *President IAH Irish Group*

Opening Address by Matthew Collins, Department of Communications, Climate Action and Environment.

SESSION I: Climate change projections and impacts – Part I

10:00 – 10:30 KEYNOTE: ‘Managing Water Resources in the Context of Climate Extremes‘– Bridget Scanlon (University of Texas, USA)

10:30 – 10:50 ‘Regional Climate Model Projections for Ireland’– Paul Nolan (ICHEC)

10:50 – 11:00 Q & A

11:00 – 11:30 *Refreshments*

SESSION II: Climate change projections and impacts – Part II

11:30 – 11:50 ‘Methods and Models to Quantify Climate-driven Changes in Groundwater Resources’ – Matt Ascott (BGS)

11:50 – 12:10 ‘Impact of climate variability on groundwater recharge to Irish bedrock aquifers’ – Elia Cantoni (TCD/iCRAG))

12:10 – 12:25 Q & A

SESSION II: One-minute poster presentations

12:25 – 13:00 Lea Duran (TCD/iCRAG)
Clodagh Gillen (University of Strathclyde/SLR)
Damien Mooney (TCD/iCRAG)
Simon Willaiam Jeggo (UCC)
Luisa Andrade (UCC/iCRAG)
Megan Dolan (NUIG)
Ella Bijkerk (TCD)
Kevin Murphy (Newcastle University/IE Consulting)
Seán Wheeler (NUIG/iCRAG)
John Paul Moore (UCD/iCRAG)

13:00 – 14:00 *Buffet lunch in Tullamore Court Hotel*

SESSION III: Impact of drought in Ireland

14:00 – 14:20 ‘Irish droughts: Past and future perspectives’ – Conor Murphy (NUIM)

14:20 – 14:40 ‘Hydrogeological Response to the 2018 Drought in Ireland’ – Philip Maher (EPA)

14:40 – 15:00 ‘The Summer of 2018 – a Group Water Schemes perspective’– Joe Gallagher (NFGWS)

15:00 – 15:20 ‘Irish Water’s Response to the 2018 Drought as Co-ordinated by the Drought Action Team, and an overview of the demand-side and supply-side actions undertaken during the June to September period’ – Tom Cuddy (Irish Water)

15:20 – 15:35 Q & A

15:35 – 16:00 *Refreshments*

SESSION IV: Drought Response 2018

16:00 – 16:20 ‘Groundwater Assets Supply-side Actions during the 2018 Drought’ – Malcolm Doak (Irish Water)

16:20 – 16:35 ‘Realignment of wellfield operations and well rehabilitation needs at the Bennetsbridge Public Water Supply’ – Henning Moe (CDM Smith)

16:35 – 16:50 ‘The Role of G1 Borehole Design in the operation and maintenance of a resilient groundwater supply’ – Gerry Baker (ARUP)

16:50 – 17:05 ‘Supply-Side Actions at the Portlaoise Public Water Supply Wellfield’– Deirdre Larkin (Atkins)

17.05 – 17:20 Q & A

17:20 *Poster Viewing & Wine Reception sponsored by City Analysts*

19:00 *Social event at Hugh Lynch’s Bar including a light evening meal, sponsored by IAH (Irish Group).*

‘Groundwater: droughts, floods and climate change’

International Association of Hydrogeologists – Irish Group
Tullamore Court Hotel, Tullamore, Co. Offaly
Tuesday 30th April – Wednesday 1st May 2019

Programme Day 2, Wednesday 1st May

08:30 – 09:00 *Tea, Coffee & Exhibits*

SESSION V: Groundwater Flooding

09:00 – 09:30 KEYNOTE: ‘Climate Change – are we going to do something about it?’ – Vincent Fitzsimons (SEPA, UK)

09:00 – 09:50 ‘Groundwater Flooding in Ireland: New Methods for Flood Monitoring and Mapping’ – Rebecca Bradford (GSI)

09:50 – 10:00 Q & A

SESSION VI: Groundwater systems in a changing climate – Part I International

10:00 – 10:30 KEYNOTE: ‘The importance of groundwater response times for understanding climate change impacts on groundwater systems’ – Mark Cuthbert (Cardiff University, UK)

10:30 – 10:50 ‘The impact of the 2015/2016 El Niño on rural water security in Ethiopia’ – Rachel Bell (BGS, UK)

10:50 – 11:00 Q & A

11:00 – 11:40 *Refreshments*

SESSION VII: Groundwater systems in a changing climate – Part II National

11:40 – 12:00 ‘Water Resource Assessment, e-flows and abstraction management’ – Conor Quinlan (EPA)

12:00 – 12:20 ‘Groundwater storage and transmission in Irish Aquifers – Implications for yield sustainability’ – Taly Hunter Williams (GSI)

12:20 – 12:40 ‘The vulnerability of peatland ecosystems to a changing climate and increases in the frequency and severity of droughts’ – Shane Regan (NPWS)

12:40 – 12:55 Q & A

12:55 Conference closing address: Sarah Blake (*Conference Secretary* – IAH Irish Group)

13:00 *Buffet lunch in Tullamore Court Hotel*

WORKSHOP: QGIS for Hydrogeologists

14:00 – 15:30 An interactive workshop outlining the use and benefits of opern-source QGIS for hydrogeologists –Shane Carey (GSI)

15:30 End of conference

Table of Contents

SESSION I

MANAGING WATER RESOURCES WITHIN THE CONTEXT OF CLIMATE EXTREMES

Bridget R. Scanlon, Zizhan Zhang*, Ashraf Rateb, Robert C. Reedy, Don Pool**; Hannes Mueller Schmied***; and Alex Sun

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**U.S.Geological Survey, Arizona Water Science Center, Tucson, Arizona, USA
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***Senckenberg Leibnitz Biodiversity and Climate Research Centre (SBiK-F), Senckenberganlage 25, 60325 Frankfurt am Main, Germany

ABSTRACT

Increasing intensity of floods and droughts is extremely challenging for water resource managers. Here we show the impacts of climate extremes on water storage using GRACE satellites, models, and monitoring data. We quantified trends in land total water storage anomalies (TWSA) in 186 river basins globally evaluating variability in storage in response to climate extremes. In the context of the global analysis, we focus on the Colorado River Basin and management approaches. Results of GRACE data show many basins responding to droughts and floods, including the Euphrates, Murray Darling, and U.S. Central Valley, and Colorado systems. Global models underestimate trends in response to floods and droughts, likely because of insufficient storage capacity to accommodate these extremes. Extending the analysis beyond the GRACE record in the Colorado Basin using modeling and monitoring data reveals decadal interval droughts interspersed with wet periods. To manage these extremes, the Colorado Basin built huge reservoirs, Lakes Powell and Mead, to store water from wet periods for droughts. In recent years, they have built a canal system to transport water from the Colorado River to cities, such as Phoenix and Tucson and irrigated areas to increase water resource sustainability by conjunctively using surface water and groundwater and managed aquifer recharge. Conjunctive use and managed aquifer recharge show great promise in moving water resources towards more sustainable management within the context of climate extremes.

INTRODUCTION

Many regions globally, particularly semiarid regions, are subjected to long-term droughts interspersed with intense floods [*Faunt et al.*, 2015] [*Long et al.*, 2013] [*van Dijk et al.*, 2013]. These climate extremes result in too much water when you don't need it and too little when you do. To address these water supply/demand disconnects, water managers generally store water from wet periods for use during droughts. Traditional storage has been provided by surface reservoirs. More recently, aquifers, particularly depleted aquifers, are being considered as storage reservoirs to manage these climate extremes [*Scanlon et al.*, 2016].

GRACE (Gravity Recovery and Climate Experiment) satellites have revolutionized the way we look at global hydrology by monitoring changes in total water storage from the atmosphere to the Moho at monthly timescales since the launch of the satellites on St. Patrick's Day in 2002. By monitoring the distance between the satellites (~ 220 km) at micron scale resolution, the GRACE satellites track variations in Earth's gravity, which is controlled primarily by movement of water because water is heavy. GRACE satellites do not monitor actual water storage but changes in water storage or anomalies relative to the period of record as anomalies (2002 – 2017). Because GRACE provides an estimate of integrated water storage throughout the vertical column, to extract water storage changes in any component requires subtraction of the other components:

$$TWSA = SnWSA + SWSA + SMSA + GWSA \qquad (1)$$

where A refers to anomaly, TWS is total water storage, SnWS is snow water storage, SWS is surface water storage, SMS is soil moisture storage, and GWS is groundwater storage. Global models are often used to estimate the different components of water storage. Many studies use GRACE data to evaluate changes in groundwater storage.

There is increasing emphasis on the use of global models to assess water resource issues. There are two basic types of models: global hydrologic models and global land surface models (LSMs). Global hydrologic models are essentially water budget models originally designed to address water scarcity concerns. Examples include the WaterGap Global Hydrologic Model (WGHM) and PC Raster Global Water Budget (PCR-GLOBWB). Global land surface models (LSMs) are more physically based, including water and energy budgets, and were developed by the climate community to provide a lower boundary for climate models. Examples include the Global Land Data Assimilation System (GLDAS) models developed by NASA. GRACE data provide an approach to assess the reliability of these global models.

The objective of our study was to examine spatiotemporal variability in water storage using GRACE and global modeling based on 186 river basins globally (Fig. 1). In addition, we focused on the Colorado River Basin to provide an example of the application of GRACE and modeling to assess water resource issues in the basin and approaches that have been used to more sustainably manage water resources within the context of increasing drought interspersed with wet cycles.

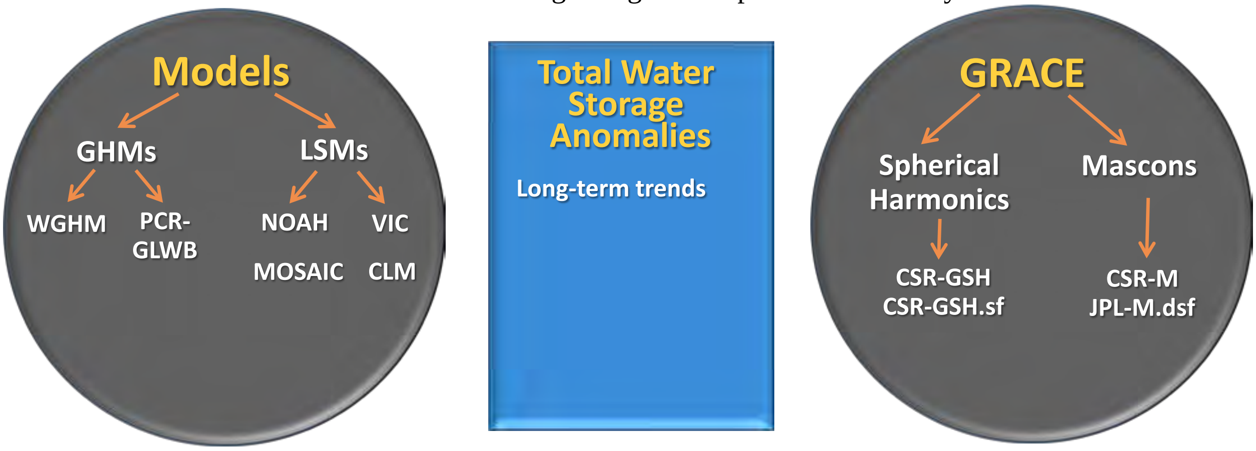

Figure 1. Flow chart showing the different global models and GRACE solutions used to evaluate spatiotemporal variability in total water storage in 186 river basins globally. GHMs: global hydrologic models; LSMs: land surface models; CSR: Univ. of Texas Center for Space Research; GSH: gridded spherical harmonic; sf: scaling factor; JPL: NASA Jet Propulsion Laboratory; dsf: downscaling factor (modified from [*Scanlon et al.*, 2018]).

RESULTS AND DISCUSSION

Trends in total water storage anomalies (TWSA) from GRACE and global models are quite variable in different basins (Fig. 2). The GRACE data show increasing trends in water storage (blue), particularly in the Amazon (43 km^3/yr), Orinoco – Parana (7 – 8 km^3/yr), Okavango-Zambezi (12 - 14 km^3/yr), Yangtze (5 km^3/yr); Murray (6 km^3/yr); and Missouri – Columbia (3 – 4 km^3/yr) (Fig. 2a). In contrast, declining trends are found in the Indus, Ganges, and Brahmaputra basins (8 – 12 km^3/yr), Euphrates (11 km^3/yr) Arkansas (5 km^3/yr); and Colorado (1 km^3/yr). Declining trends in the Ganges region are attributed to groundwater depletion because this region was not subjected to long-term drought. Modeled trends in TWSA differ from those from GRACE. For example, most models simulate declining trends in the Amazon up to 66 km^3/yr (PCR-GLOBWB) with the exception of WGHM which simulates a slight rising trend (11 km^3/yr) in contrast to the rising trend of 43 km^3/yr from GRACE. Similar discrepancies are found in the neighboring Parana and Orinoco basins. Models greatly underestimate the rising trends in the Okavango and Zambezi basins because they do not simulate flows in endorheic basins. In many cases the GRACE and modeled trends are in the same direction but the modeled trends are generally much lower in magnitude.

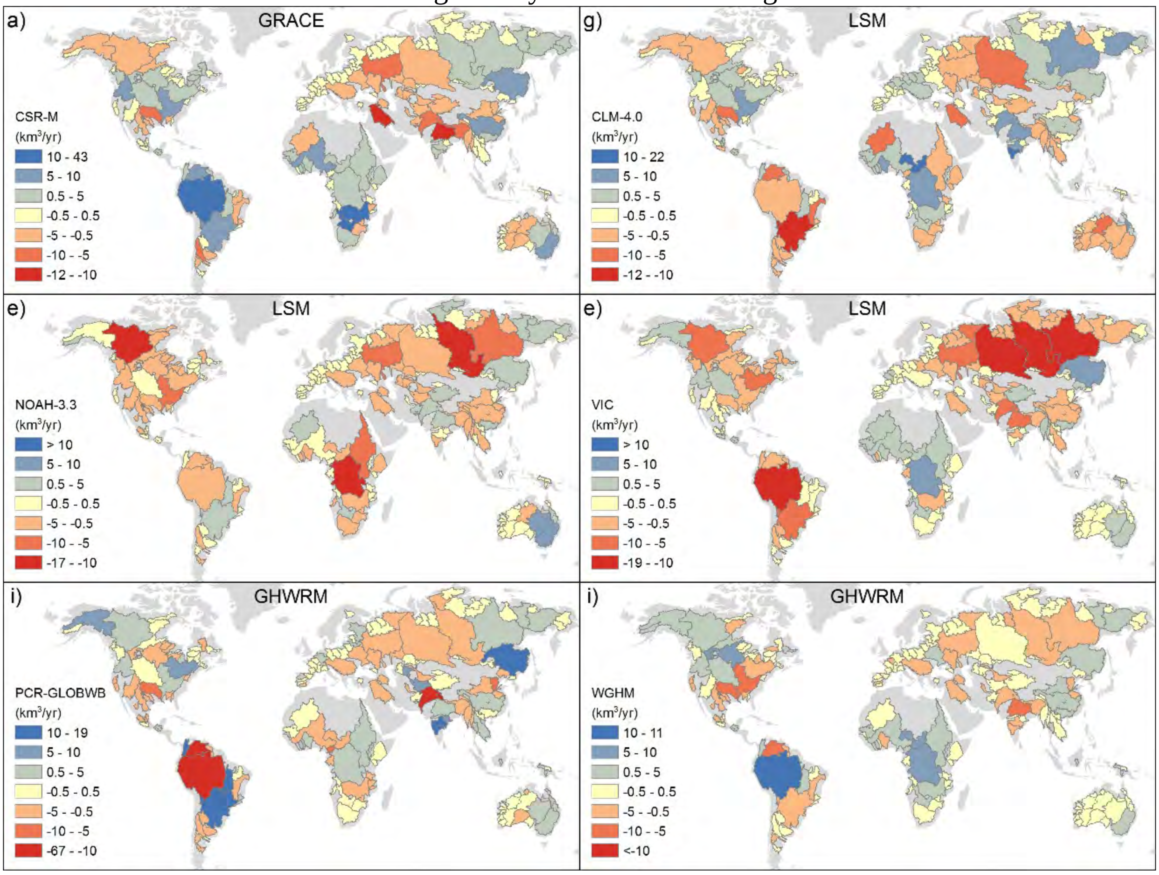

Figure 2. Trends in total water storage anomalies (TWSA) from GRACE mascons (M) based on Univ. of Texas Center for Space Research (CSR) data (CSR-M); land surface models, including CLM-4.0, NOAH-3.3, and VIC; and global hydrologic models (PCR-GLOBWB and WGHM) (modified from [*Scanlon et al.*, 2018]).

Time series of TWSA provide an indication of interannual variability in GRACE and modeled results (Fig. 3). For example, the Euphrates was subjected to a drought in 2007 – 2009 that was originally attributed to groundwater depletion for irrigation pumpage [*Voss et al.*, 2013] but later attributed to declines in surface reservoir storage [*Longuevergne et al.*, 2013], and reservoir storage and groundwater depletion mostly from natural response to drought rather than pumpage [*Mulder et al.*, 2014]. This example demonstrates the difficulty of interpreting GRACE TWSA and the value of using ground-based data to constrain the interpretation. The Murray Darling Basin also shows the large increase in storage in 2010 after the Millennium drought and the more muted recovery simulated by the models relative to GRACE data.

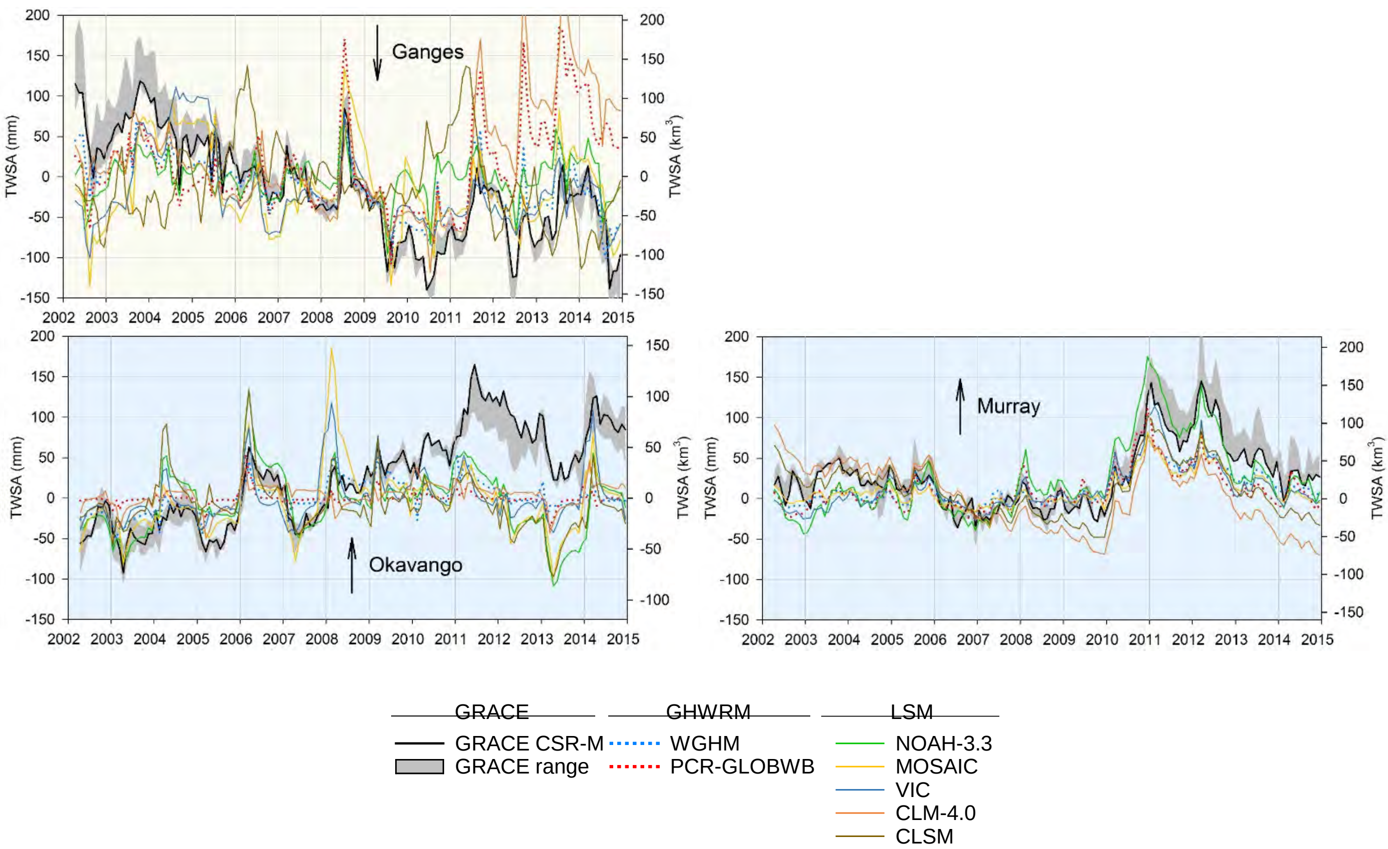

Figure 3. Example time series of total water storage anomalies (TWSA) from GRACE (black line and gray shaded region) and from models (colored lines) for the Ganges and Euphrates (decreasing trends) and Okavango, and Murray (increasing trends) basins. The declining trend in the Ganges is attributed to groundwater pumpage and in the Euphrates in response to the 2007 – 2009 drought. Rising trend in the Okavango is attributed to increased precipitation and accumulation in endorheic basins and to recovery from the Millennium drought in the Murray Basin (modified from [*Scanlon et al.*, 2018]).

The Colorado Basin represents another example where the interpretation of the GRACE signals has changed over time. The initial analysis attributed decreases in TWSA from GRACE primarily to groundwater pumpage [*Castle et al.*, 2014] that was also highlighted in National Geographic (2014). However, U.S. Geological Survey water use records suggest little groundwater pumpage in the Upper Colorado River Basin, which prompted us to re-evaluate the analysis for this basin [*Scanlon et al.*, 2015]. Extending the analysis of total water storage anomalies beyond the GRACE period using models and ground-based data, we see that the Colorado Basin has been subjected to droughts at approximately decadal intervals with limited water storage recovery during intervening wet periods (Fig. 4). In the Upper Basin most water for irrigation and other sectors is derived from surface water whereas in the lower basin water use is derived almost equally from groundwater and surface water. Total water storage variability in the upper basin can be accounted for by variations in snow, surface water, and soil moisture storage. Groundwater is important in the lower basin where the cities of Phoenix and Tucson are located and where irrigated agriculture is widespread. However, analysis of up to 1000 groundwater level records shows that groundwater storage is responding naturally to these variations in climate (wet and dry cycles) and groundwater depletion from irrigation is mostly limited to basins that do not have access to surface water. These results are also supported by ground-based gravity surveys in the urban areas showing increases in storage in recent times.

Water resources management has changed within the past couple of decades with development of the Central Arizona Project (CAP), a 540 km pipeline delivering water from the Colorado River (Fig. 5). Therefore, irrigators have been using surface water where they have access to CAP water. Not only has this offset the use of groundwater but has increased groundwater storage through recharge from flood irrigated fields. In addition, managed aquifer recharge projects have been developed in different Active Management Areas (AMAs), actively recharging depleted aquifers using spreading basins (Figs. 5, 6a). The only regions where groundwater is continuing to decline is in basins that do not have access to surface water. These regions are still experiencing declines of up to 1.3 m/yr (Fig. 6b).
The Lower Colorado River Basin demonstrates a proactive, engineering approach to managing from climate extremes. The process involved development of demonstration recharge basins to show the feasibility of MAR, and changes in regulations to accommodate MAR. The big question is with declining storage in the main reservoirs (Powell and Mead) from long-term drought, what will happen if CAP water cannot be delivered? Will farmers revert to groundwater pumping and its related depletion?

These management approaches will also be increasingly adopted in California since the 2014 legislation related to the Sustainable Groundwater Management Act. California has been conjunctively managing surface water and groundwater in the Central Valley for decades with water use shifting from approximately 70% surface water during wet periods to 70% groundwater during droughts [*Scanlon et al.*, 2016]. While MAR basins have been active in some regions since the 1960s, they will likely expand in the future. In addition, California is subjected to intense precipitation resulting from atmospheric rivers and is evaluating flood MAR in the winter in fallowed or perennial crops (almonds and vineyards) to recharge depleted aquifers [*Dahlke et al.*, 2018].

While in the past we have focused on natural recharge and understanding the dynamics of aquifers, we will be increasingly moving towards engineering solutions to manage climate extremes. Conjunctive use of surface water and groundwater and managed aquifer recharge are valuable approaches to managing these climate extremes.

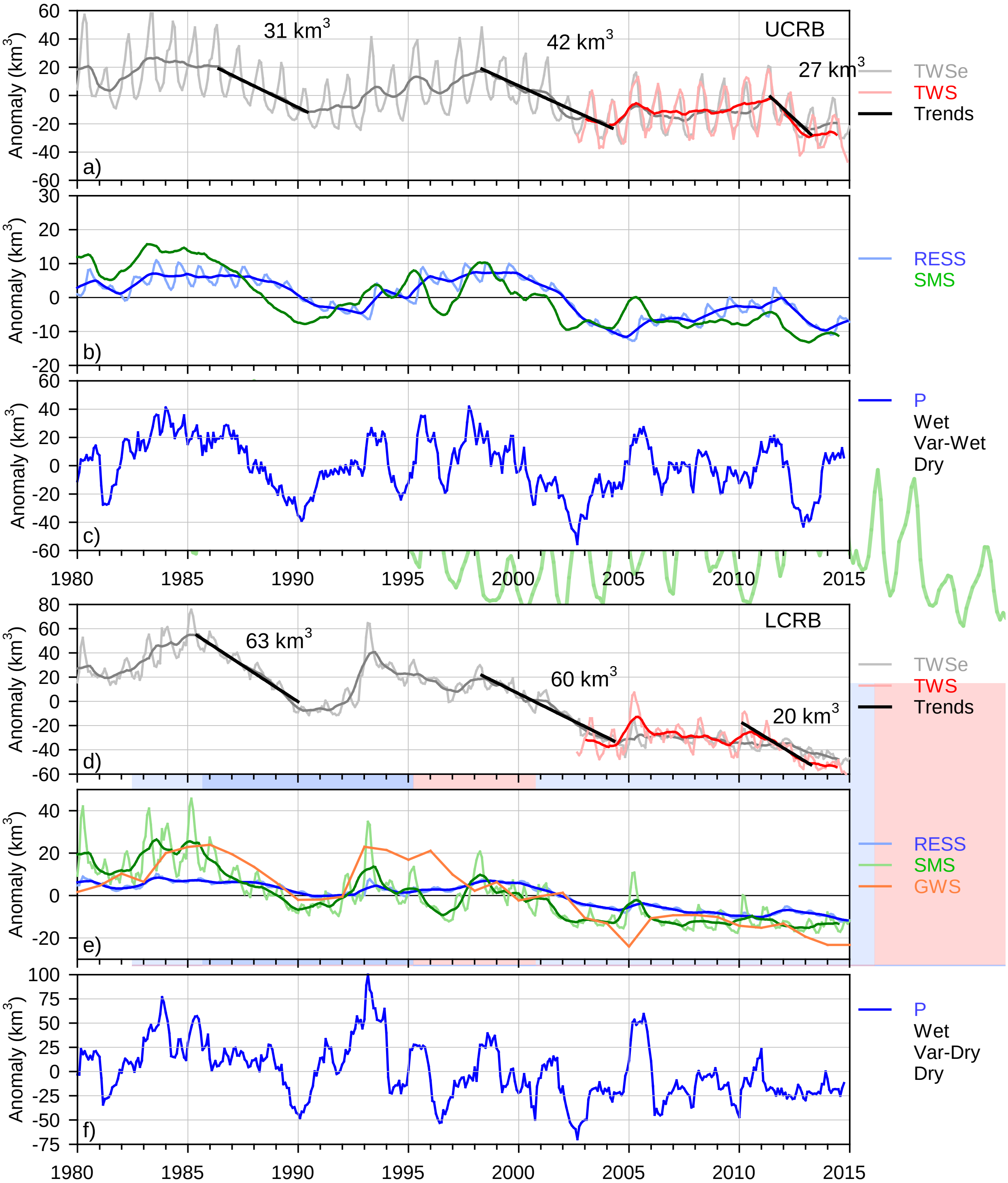

Figure 4. Time series of estimated total water storage (TWSe) from models and monitoring, GRACE total water storage (TWS), reservoir storage (RESS), soil moisture storage, (SMS from GLDAS), precipitation (P), and groundwater storage (GWS) in the (a–c) Upper (UCRB) and (d–f) Lower (LCRB) Colorado River Basin. Values represent anomalies relative to the 1980–2014 water year means. Shaded areas in Figures 4c and 4f qualitatively characterize periods as wet, variable to wet (Var-Wet), variable to dry (Var-Dry), or dry with respect to 1980–2014 mean precipitation (modified from [*Scanlon et al.*, 2015]).

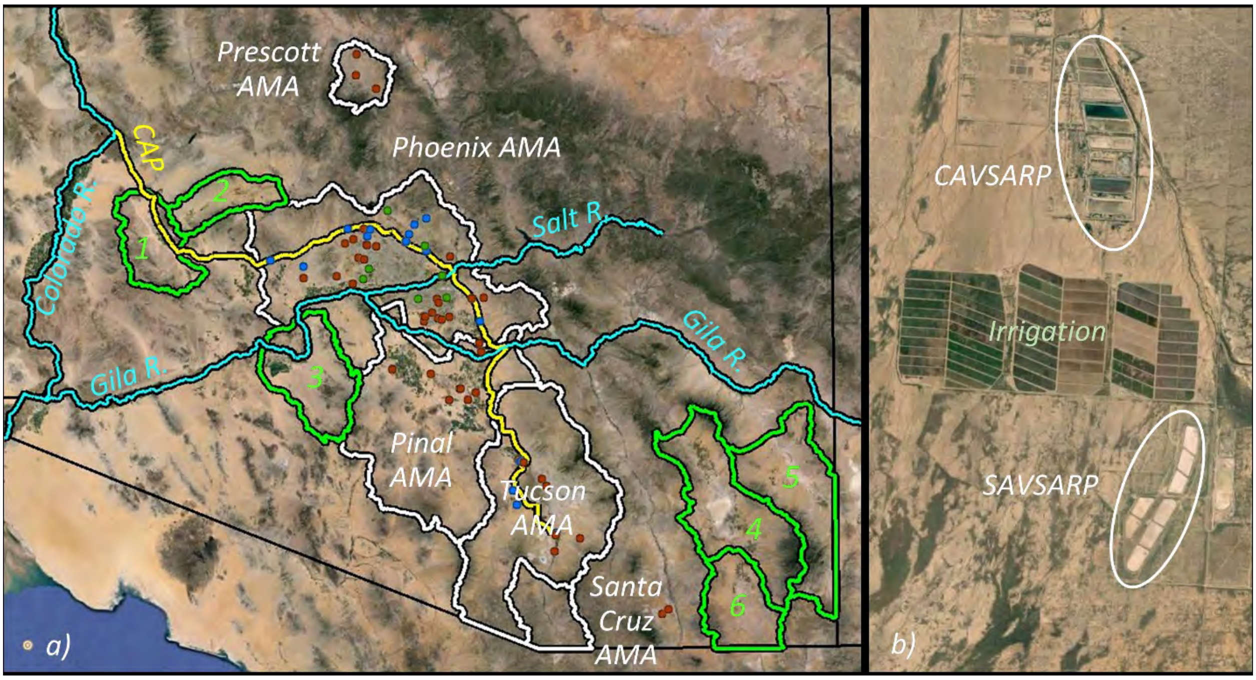

Figure 5 (a) Infrastructure to support conjunctive use and managed aquifer recharge (MAR) in Arizona. The active management areas (AMAs, outlined in white) include Prescott, Phoenix, Pinal, Tucson, and Santa Cruz. Basins outlined in green are irrigated basins without access to surface water from the Colorado River: 1. Ranegras; 2. McMullen Valley; 3. Gila Bend; 4. Willcox Basin; 5. San Simon Valley; and 6. Douglas Basin. The Colorado, Salt, and Gila are the main rivers in the region. The Central Arizona Project (CAP) aqueduct delivers water from Lake Havasu on the Colorado River to Phoenix, Pinal, and Tucson AMAs. Managed aquifer recharge locations (spreading basins) are shown with water sources from CAP (blue circles), reclaimed municipal waste water (MWW, brown circles), and both sources (green circles, which may also include local surface water). (b) Image showing the Central and Southern Avra Valley Storage and Recovery Projects (CAVSARP, SAVSARP) spreading basins and irrigated region in between, located in the Tucson AMA (modified from [*Scanlon et al.*, 2016]).

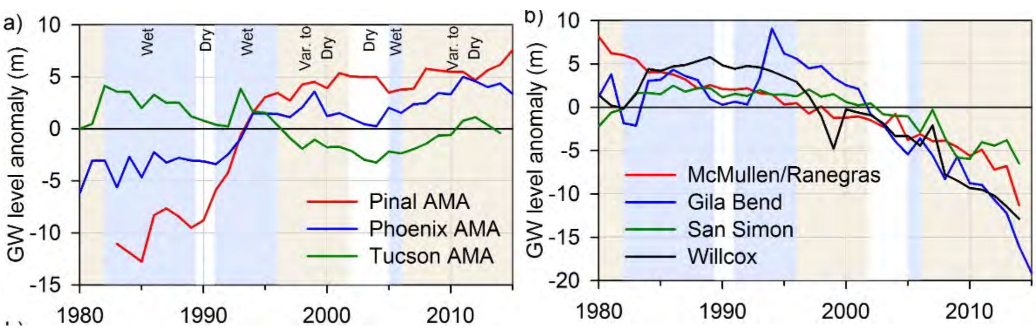

Figure 6. Composite groundwater level hydrographs (a) in the Phoenix, Pinal, and Tucson active management areas (AMAs), and (b) in areas outside the CAP delivery zones (McMullen/Ranegras (1, 2), Gila Bend (3), San Simon (5), and Willcox (4) basins). Numbers in parentheses represent locations of basins in figure 2. Hydrographs in the AMAs represent the mean anomalies for 888 wells in the Phoenix

AMA, 583 wells in the Pinal AMA, 995 wells in the Tucson AMA (2466 wells total). The Avra Valley hydrograph represents a subset of 251 wells in the Tucson AMA. Source: Arizona Department of Water Resources Groundwater Site Inventory (ADWRGWSI, https://gisweb.azwater.gov/waterresourcedata/GWSI.aspx) (modified from [*Scanlon et al.*, 2016]).

SUMMARY

GRACE satellites and global models provide excellent approaches to assess water resources at a global scale. GRACE monitors changes in total water storage from the land surface to depth. Decreasing trends are found in regions subjected to groundwater depletion (e.g., Ganges region), drought (e.g., Euphrates, Colorado). In contrast increasing trends are found in the Amazon region, Okavango-Zambezi region (endorheic basins), Yangtze (filling Three Gorges reservoir), and Murray Darling (recovery from drought). Global models generally underestimate both declining and rising trends, which are attributed to missing modeled storage compartments (e.g., surface water and groundwater in land surface models) or insufficient storage capacity to accommodate the trends. Several examples highlight the difficulties of interpreting GRACE total water storage changes and the value of additional data in interpreting the trends.

Total water storage trends in the Colorado Basin were initially interpreted as due to groundwater pumpage; however, more detailed analysis with ground-based monitoring and regional modeling emphasize natural groundwater response to droughts. Conjunctive use of surface water and groundwater and managed aquifer recharge have moved the system towards more sustainable water resources management. Conjunctive use and storage in depleted aquifers will become increasingly important for more sustainable management within the context of climate extremes.

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REGIONAL CLIMATE MODEL PROJECTIONS FOR IRELAND

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ABSTRACT

The method of Regional Climate Modelling (RCM) was employed to assess the impacts of a warming climate on the 21st-century climate of Ireland. The RCM simulations were run at high spatial resolution (6 & 4km), thus allowing a better evaluation of the local effects of climate change. To address the issue of uncertainty, a multi-model ensemble approach was employed. Through the ensemble approach, the uncertainty in the projections can be partially quantified, thus providing a measure of confidence in the predictions. Simulations were run for a reference period 1981–2000 and future period 2041–2060. Differences between the two periods provide a measure of climate change. The COSMO-CLM and WRF RCMs were used to downscale the following CMIP5 global datasets; CNRM-CM5, EC-EARTH, HadGEM2-ES, MIROC5 and MPI-ESM-LR. To account for the uncertainty in future emissions, the RCP 4.5 & 8.5 scenarios were used to simulate the future climate.

Results for mid-century indicate an increase of 1–1.7°C in mean annual temperatures, with the largest increases seen in the east. Warming is enhanced for the extremes (i.e. hot or cold days). Averaged over the whole country, the number of frost days is projected to decrease by over 50%. The projections indicate an average increase in the length of the growing season of over 35 days per year. Results show significant projected decreases in mean spring and summer precipitation amounts by mid-century. The projected decreases are largest for summer, with "likely" reductions ranging from 0% to 20%. The frequencies of heavy precipitation events show notable increases (approximately 20%) during the winter and autumn months. The number of extended dry periods is projected to increase substantially during autumn and summer.

The RCM simulations are currently being extended to cover the time period 1976-2100. Moreover, the future climate is simulated under the full range of RCP scenarios (2.6, 4.5, 6.0 & 8.5). The RCM ensemble will be improved by using coupled atmosphere-ocean-wave RCMs to downscale CMIP6 global simulations. All updated simulations are run with a high-resolution grid spacing of 4km.

Regional Climate Modelling

The impact of increasing greenhouse gases and changing land use on climate change can be simulated using Global Climate Models (GCMs). However, long climate simulations using GCMs are currently feasible only with horizontal resolutions of ~50 km or coarser. Since climate fields such as precipitation, wind speed and temperature are closely correlated to the local topography, this is inadequate to simulate the detail and pattern of climate change and its effects on the future climate of Ireland. The Regional Climate Model (RCM) method dynamically downscales the coarse information provided by the global models and provides high-resolution information on a subdomain covering Ireland. The computational cost of running the RCM, for a given resolution, is considerably less than that of a global model. The approach has its flaws; all models have errors, which are cascaded in this technique, and new errors are introduced via the flow of data through the boundaries of the regional model. Nevertheless, numerous studies have demonstrated that high-resolution RCMs improve the simulation of fields such as precipitation (Bieniek et al., 2015, Kendon et al., 2012, 2014, Lucas-Picher et al., 2012) and topography-influenced phenomena and extremes with relatively small spatial or short temporal character (Feser et al., 2011; Feser and Barcikowska, 2012; Shkol'nik et al., 2012;

Flato et al., 2013). An additional advantage is that the physically based RCMs explicitly resolve more small-scale atmospheric features and provide a better representation of convective precipitation (Rauscher et al., 2010) and extreme precipitation (Kanada et al., 2008). Other examples of the added value of RCMs include improved simulation of near-surface temperature (Di Luca et al., 2016, Feser, 2006), European storm damage (Donat et al., 2010), strong mesoscale cyclones (Cavicchia and Storch, 2011), North Atlantic tropical cyclone tracks (Daloz et al., 2015) and of near-surface wind speeds (e.g. Kanamaru et al., 2007), particularly in coastal areas with complex topography (Feser et al., 2011; Winterfeldt et al., 2011). The IPCC have concluded that there is “high confidence that downscaling adds value to the simulation of spatial climate detail in regions with highly variable topography (e.g., distinct orography, coastlines) and for mesoscale phenomena and extremes” (Flato et al., 2013).

Climate Models and Methods

The future climate of Ireland was simulated at high spatial resolution (4 & 6km) using the COSMO-CLM (v4.0 & 5.0) and WRF (v3.6) RCMs. The COSMO-CLM regional climate model is the COSMO weather forecasting model in climate mode (www.clm-community.eu, Rockel et al., 2008). The COSMO model (www.cosmo-model.org) is the non-hydrostatic operational weather prediction model used by the German Weather Service (DWD). The WRF model (www.wrf-model.org) is a numerical weather prediction system designed to serve atmospheric research, climate and operational forecasting needs. The WRF simulations of the present study adopted the Advanced Research WRF (ARW) dynamical core, with development led by the US National Center for Atmospheric Research (NCAR).
Projections for the future Irish climate were generated by downscaling the following CMIP5 global datasets; the UK Met Office’s Hadley Centre Global Environment Model version 2 Earth System configuration (HadGEM2-ES) GCM, the EC-Earth consortium GCM, the CNRM-CM5 GCM developed by CNRM-GAME (Centre National de Recherches Météorologiques—Groupe d’études de l’Atmosphere Météorologique) and Cerfacs (Centre Européen de Recherche et de Formation Avancée), the Model for Interdisciplinary Research on Climate (MIROC5) GCM developed by the MIROC5 Japanese research consortium and the MPI-ESM-LR Earth System Model developed by the Max Planck Institute for Meteorology. To account for the uncertainty arising from the estimation of future global emission of greenhouse gases, downscaled GCM simulations based on two Representative Concentration Pathways (RCP4.5 and RCP8.5) were used to simulate the future climate of Ireland.

The RCMs were driven by GCM boundary conditions with the following nesting strategies; GCM to 50km to 18km to 4km (COSMO v4), GCM to 18km to 4km (COSMO v5) and GCM to 54km to 18km to 6km (WRF). For the current study, only 4km and 6km grid spacing RCM data are considered. The higher resolution data allows sharper estimates of the regional variations of climate projections. The climate fields of the RCM simulations were archived at 3-h intervals. The WRF model domains are shown in Figure 1. The COSMO-CLM 50, 18 and 4km domains are similar (not shown).

An overview of the simulations is presented in Table 1; the rows present information on the RCM, corresponding downscaled GCM and number of realizations, nesting strategy, historical simulated period, future simulated period, RCP details and the number of ensemble comparisons. The GCM realisations result from running the same GCM with slightly different initial conditions, i.e. the starting date of historical simulations. Data from two time-slices, 1981–2000 (the control) and 2041–2060, were used for analysis of projected changes in the mid-21st-century Irish climate. These periods were chosen because they are the longest decadal time periods common to all RCM simulations. The historical period was compared with the corresponding future period for all simulations within the same RCM-GCM group. This results in future anomalies for each model run; that is, the difference between future and past.

To create a large ensemble, all RCM outputs were regridded to a common 6-km grid over Ireland using the method of bilinear interpolation. This results in 24 RCP4.5 and 24 RCP8.5 ensemble comparisons. The relatively large number of comparisons allows for the uncertainty of the projections to be partially quantified, providing a measure of confidence in the predictions.

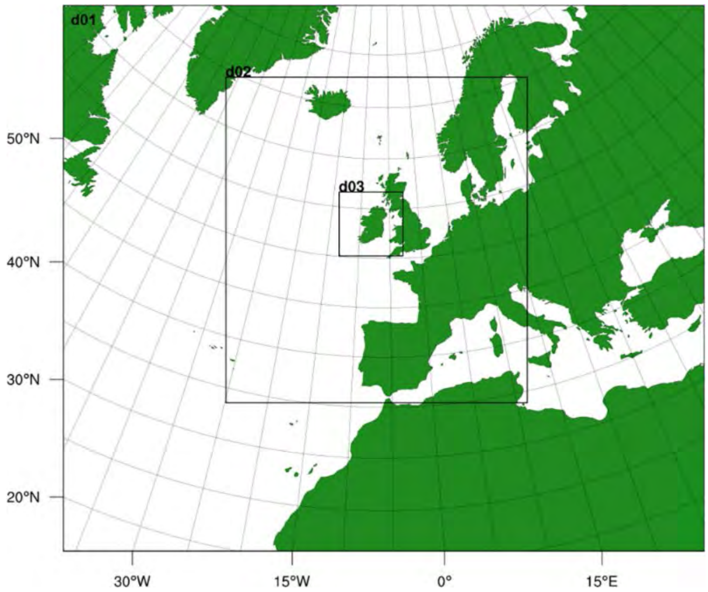

Figure 1. The WRF model domains. The d01, d02 and d03 domains have 54, 18 and 6 km grid-spacings, respectively.

RCM	GCM (# ensemble members, realizations)	Nesting Strategy	Historical	RCP4.5 # Ens. Comparisons	RCP8.5 # Ens. Comparisons
COSMO 4	**HadGEM2-ES (r1i1p1)**	**50 - 18 - 4km**	**1980-2000**	**2020-2060 (1)**	**2020-2060 (1)**
COSMO 4	**EC-Earth x3 (r1i1p1, r13i1p1 & r14i1p1)**	**50 - 18 - 4km**	**1980-2005**	**2020-2060 (9)**	**2020-2060 (9)**
WRF	**EC-Earth x3 (r1i1p1, r13i1p1 & r14i1p1)**	**54 - 18 - 6km**	**1980-2005**	**2020-2060 (9)**	**2020-2060 (9)**
COSMO 5	**EC-Earth (r1i1p1)**	**18 - 4km**	**1975-2005**	**2006-2100 (1)**	**2006-2100 (1)**
COSMO 5	**MPI-ESM-LR (r1i1p1)**	**18 - 4km**	**1975-2005**	**2006-2100 (1)**	**2006-2100 (1)**
COSMO 5	**CNRM-CM5 (r1i1p1)**	**18 - 4km**	**1975-2005**	**2006-2100 (1)**	**2006-2100 (1)**
COSMO 5	**HadGEM2-ES (r1i1p1)**	**18 - 4km**	**1975-2005**	**2006-2100 (1)**	**2006-2100 (1)**
COSMO 5	**MIROC5 (r1i1p1)**	**18 - 4km**	**1975-2005**	**2006-2100 (1)**	**2006-2100 (1)**

Table1. Details of the ensemble RCM simulations. The rows present information on the RCM used, corresponding downscaled GCM and number of realizations, nesting strategy, historical simulated period, future simulated period, RCP details and the number of ensemble comparisons.

The RCMs were validated by downscaling ERAInterim reanalyses and the GCM datasets for the period 1981-2000, and comparing the output against observational data. Extensive validations were carried out to test the ability of the RCMs to accurately model the climate of Ireland. Results confirm that the output of the RCMs exhibit reasonable and realistic features as documented in the historical data record and consistently demonstrate improved skill over the GCMs (e.g., Nolan et al., 2014, 2015

& 2017, Flanagan et al., 2019 and Werner et al., 2019). Moreover, an increase in the spatial resolution of the RCMs resulted in a general increase in skill.

Regional Climate Projections for Ireland

Temperature projections show a clear west-to-east temperature gradient, with the largest increase seen in the east (see Figure 2a). This trend is consistent with previous studies (e.g., Nolan, 2015, O'Sullivan et al. 2015, Glesson et al, 2013) and with all RCPs, RCM-GCM simulations and time periods assessed to-date. The relatively large ensemble allows for a better understating of climate change uncertainty. For example, the standard deviation of ensemble projections of temperature (Figure 2b) quantifies the spread (or disagreement) between simulations. The projected warming was found to be enhanced for the extremes (i.e. hot or cold days). Averaged over the whole country, the number of frost days is projected to decrease by over 50%. The projections indicate an average increase in the length of the growing season of over 35 days per year.

Rainfall is projected to increase during winter and autumn and decrease during summer and over the full year (Figure 3a). Again, this is consistent with previous research (e.g., Nolan, 2015, 2017, Dunne et al., 2008, McGrath et al., 2005). The standard deviation of precipitation projections (Figure 3b) demonstrates a larger spread when compared to temperature. Nevertheless, most ensemble members (> 85%) agree on the sign of the projected change. The frequencies of heavy precipitation events show notable increases (approximately 20%) during the winter and autumn months. The number of extended dry periods is projected to increase substantially during autumn and summer. Specific humidity is expected to increase during all seasons with the largest increases noted during the winter months (Figure 4). Projections of 2m relative humidity show small increases during winter and decreases during summer.

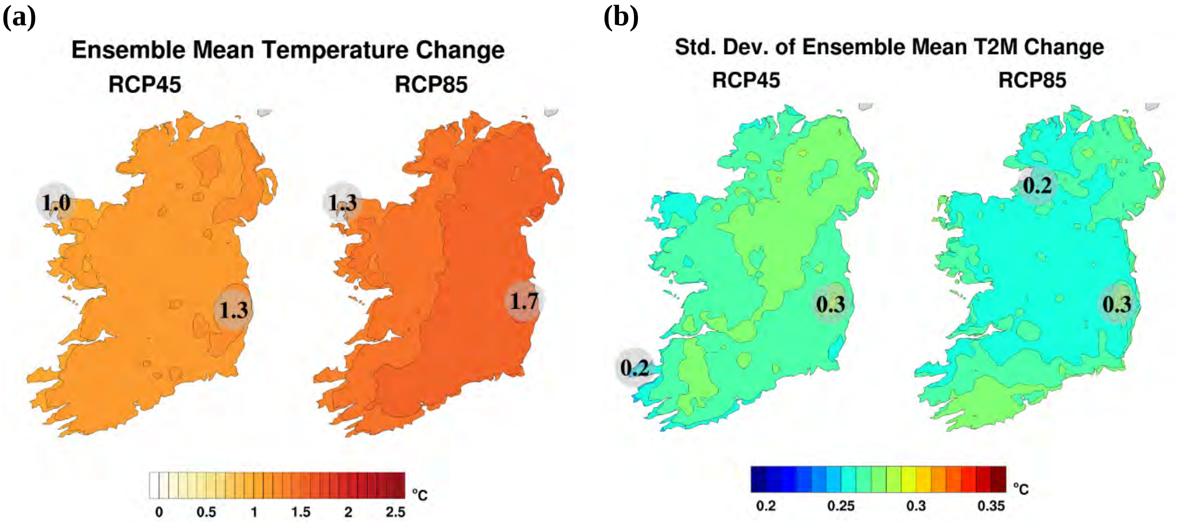

Figure 2. (a) Mean and **(b)** Standard Deviation of Ensemble of 2m Temperature Projections. In each case, the future 20-year period 2041-2060 is compared with the past period 1981-2000. The numbers included on each plot are the minimum & maximum values

Wind Speeds are projected to decrease during spring, summer and over the full year (Figure 5). Small increases are noted for winter but more work and simulations are required as there exists some disagreement between RCMs for winter wind speed. The wind speed projections are broadly consistent with previous studies (e.g., Nolan 2011 & 2014, Dunne et al., 2008).

Current RCM research

Current RCM research aims to reduce climate change projection uncertainty and provide sharper estimates of expected climate change in the in the decades ahead. This is being achieved by running a large ensemble of high-resolution downscaled simulations using the most up-to-date RCMs (both standard and coupled atmosphere-ocean-wave), CMIP6 GCMs and all four "tier-1" RCPs (SSP1-2.6, SSP2-4.5, SSP3-7.0 & SSP5-8.5). Additionally, the accuracy and usefulness of the model predictions will be enhanced by increasing the model resolution (< 4km) and using fully coupled atmosphere-ocean-wave RCMs. Preliminary RCM projection results are in line with previous work with enhanced temperature rises by end-of-century (Figure 6), wetter winters with a clear north-west to south-east gradient (Figure 7) and a general decrease in wind speeds during summer. The preliminary results of Figures 6 & 7 were obtained by extending the projections of Table 1 to cover the period 1975-2100.

(a) **(b)**

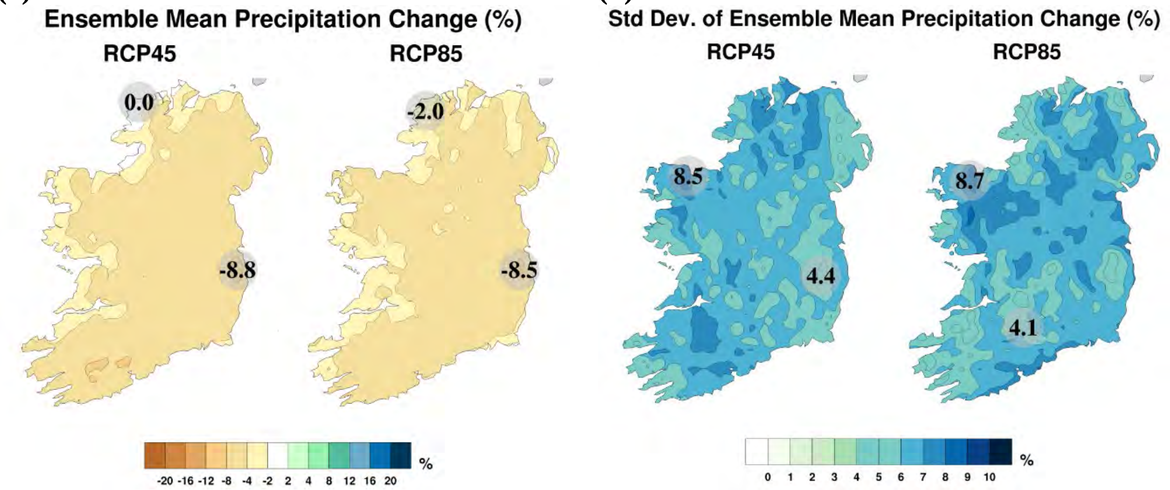

Figure 3. (a) Mean and **(b)** Standard Deviation of Ensemble of Precipitation Projections (%). In each case, the future period 2041-2060 is compared with the past period 1981-2000.

(a) **(b)**

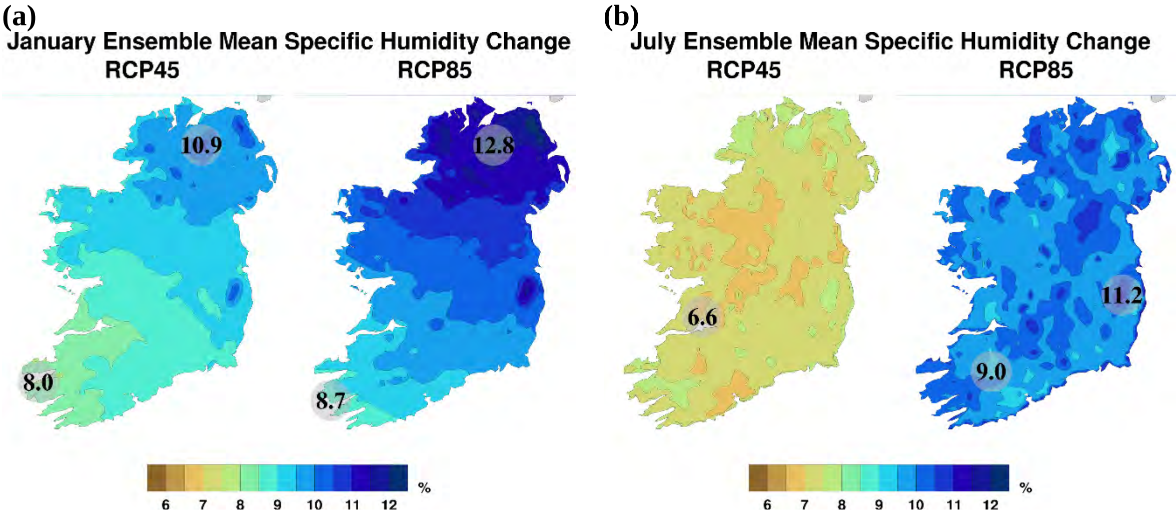

Figure 4. Mean Ensemble Projections of Specific Humidity (%) for **(a)** January and **(b)** July. In each case, the future 20-year period 2041-2060 is compared with the past period 1981-2000.

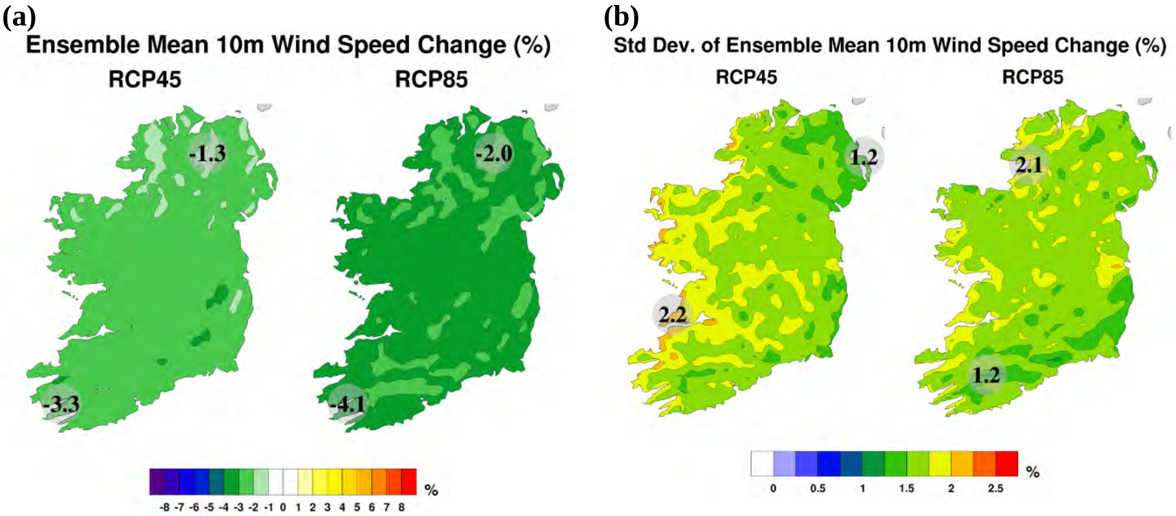

Figure 5. (a) Mean and **(b)** Standard Deviation of Ensemble of 10m Wind Speed Projections (%). In each case, the future 20-year period 2041-2060 is compared with the past period 1981-2000.

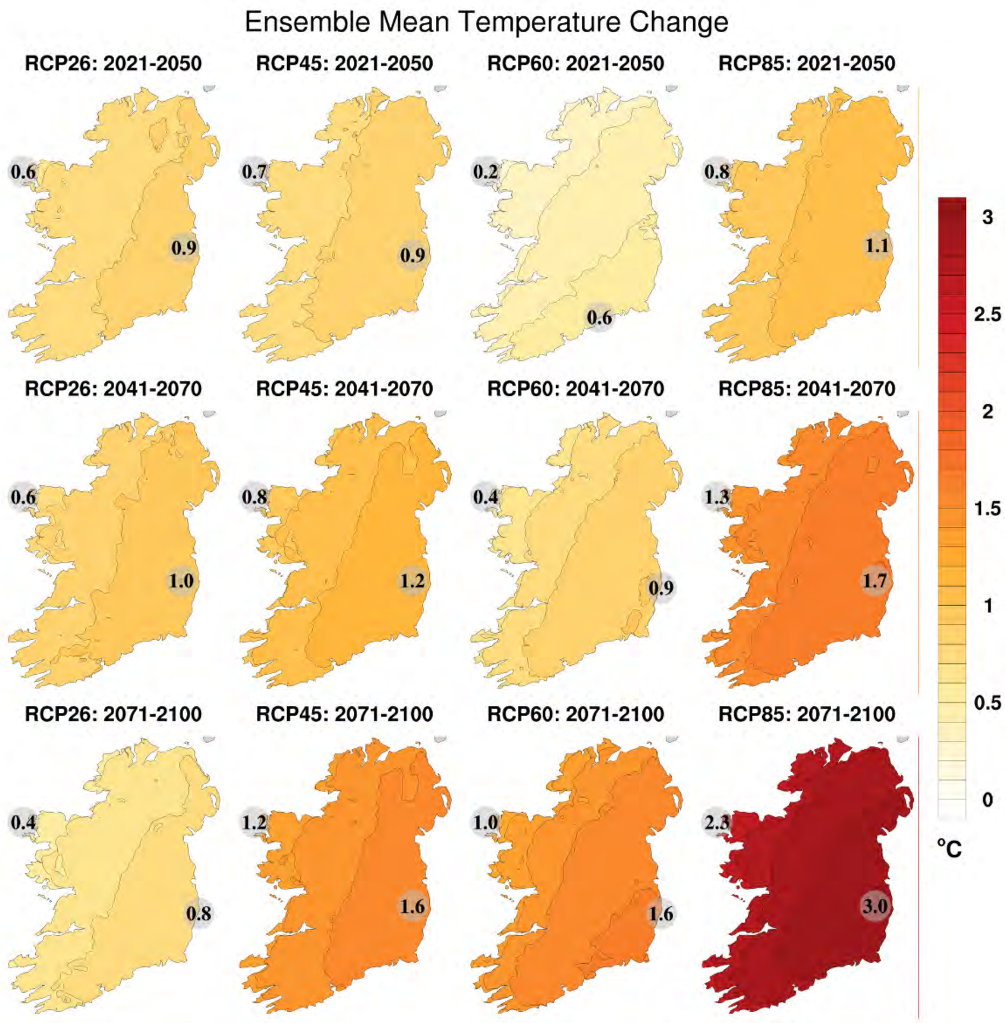

Figure 6. Updated RCM Ensemble Projections of 2M Temperature. All RCM ensemble members were run with 4km grid spacing. In each case, the future 30-year period is compared with the past period 1976-2005.

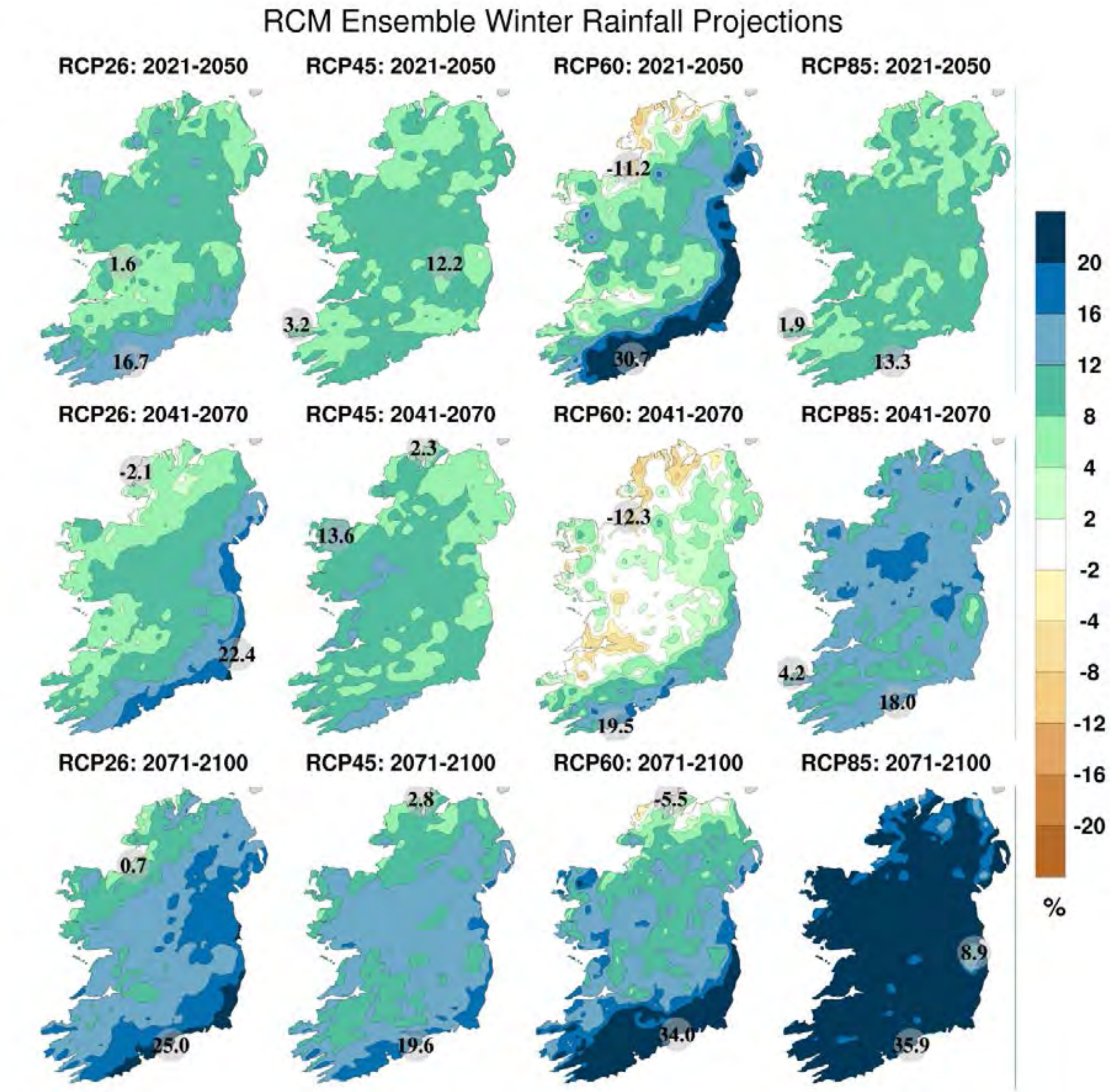

Figure 7. Updated RCM Ensemble Projections of Winter Rainfall (%). All RCM ensemble members were run with 4km grid spacing. In each case, the future 30-year period is compared with the past period 1976-2005.

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METHODS AND MODELS TO QUANTIFY CLIMATE-DRIVEN CHANGES IN GROUNDWATER RESOURCES

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ABSTRACT

Understanding climate-driven changes in groundwater resources is essential for future water resources management. In this paper, we review methods and models developed to quantify past, present and future climate-driven changes in groundwater resources, and provide an outlook for future research and practice. The Standardised Groundwater level Index (SGI) has been an effective methodology for quantifying historic groundwater resource status across different sites using observed historical data. However, the paucity of groundwater level data means that modelling groundwater levels may also be required. Lumped parameter models such as AquiMod have been shown to be effective at reconstructing groundwater levels at observation boreholes beyond historic records. These models have also been used for seasonal forecasting of groundwater levels and quantifying impacts of climate change. Major challenges remain in linking indicators of groundwater resource status (i.e. levels) with downstream impacts at both the high and low end of the hydrograph. An example of this is provided by estimating impacts of climate change on yields at abstraction boreholes during drought. As well as linking groundwater levels to impacts, future research should explore the full range of the SGI and apply the latest climate model data to AquiMod models. Access to both live groundwater level observations and high performance computing facilities would allow the methods reviewed here to be applied automatically, providing real-time hydrogeological data services.

INTRODUCTION

Understanding climate-driven changes in groundwater resources is essential for water resources management. Quantifying historical changes in groundwater levels can help contextualise current groundwater resource status (Jackson et al., 2016). Assessment of present or near future changes is also beneficial for short-term operational groundwater resource management (Mackay et al., 2015), whilst quantifying impacts of climate change over the next 25-50 years is needed for longer-term strategic planning (Water UK, 2016).

Whether considering groundwater resources in the past, present or future, appropriate methods and models are required to quantify changes. This paper reviews some of these approaches recently developed. The use of the Standardised Groundwater level Index (SGI) to quantify historical changes in groundwater levels at observation boreholes across multiple sites is reviewed. We then review the use of a lumped parameter model, AquiMod, for reconstruction, forecasting and climate change modelling of groundwater levels. Using a case study of quantifying the impacts of climate change on yields at abstraction boreholes during drought, we highlight the challenges of translating changes in groundwater levels to meaningful metrics of impact. Finally, we provide an outlook for future research and practice using these approaches.

THE STANDARDISED GROUNDWATER LEVEL INDEX (SGI) – A METHOD FOR QUANTIFYING CLIMATE-DRIVEN CHANGES IN HISTORICAL GROUNDWATER LEVELS

Understanding the response in groundwater levels to drought and flood events across multiple sites requires comparisons between standardised groundwater level hydrographs. Whilst there are numerous methods for the development of standardised indices for streamflow and precipitation (Zargar et al., 2011), standardised indices for groundwater levels have only recently been developed. Applied to monthly time series of groundwater levels at 14 boreholes in Great Britain, Bloomfield and Marchant (2013) developed the Standardised Groundwater level Index (SGI). In brief, a normal-scores transform is applied to all groundwater level data for each separate month of a year, and the transformed scores for each month are merged back to form a SGI time series. Values of the SGI below zero are considered to be drier, and above zero wetter, with -1/1 often being used as an arbitrary threshold for drought/flood. Figure 1 shows groundwater level time series and the resultant SGI time series for these sites. By applying the normal-scores transform to each month separately, the SGI is a de-seasonalised time series that shows departures from monthly mean groundwater levels and so enables the quantification of temporally coherent groundwater deficits or excesses between sites.

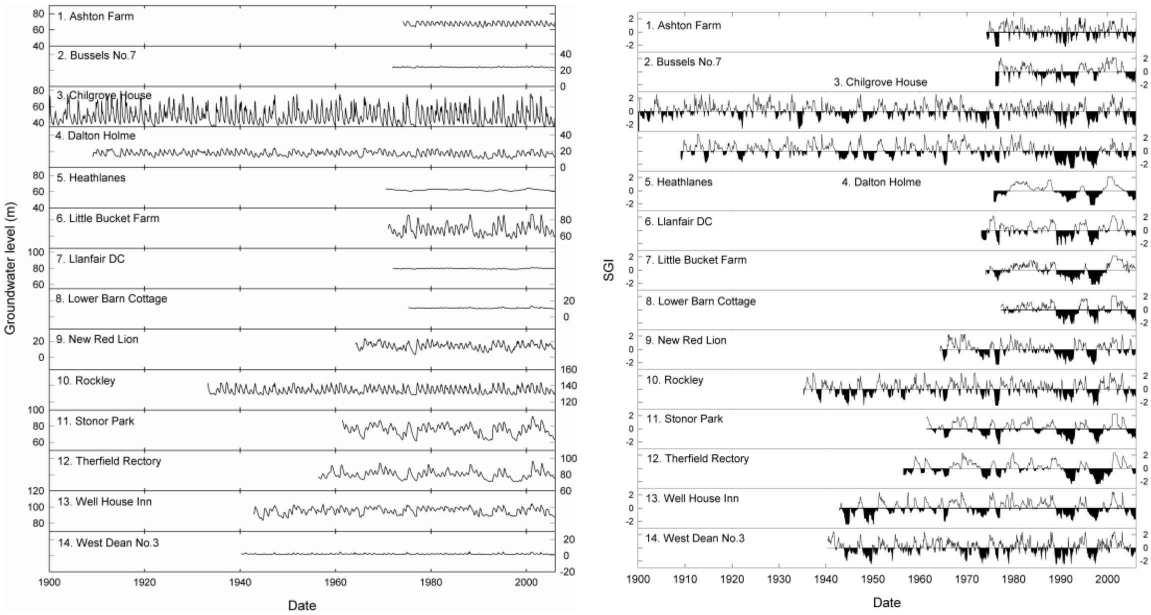

Figure 1: Groundwater level time series (left) and SGI time series (right) for 14 sites in Great Britain. Reproduced after Bloomfield and Marchant (2013).

This is particularly evident when presenting SGI values < 0 as a heatmap (Figure 2), where the spatial coherence of droughts in the 1990s is clear. It is also interesting to note that some sites have more persistence and memory in the SGI (e.g. site 5 vs site 1), associated with both different recharge processes and aquifer flow and storage characteristics (Bloomfield and Marchant, 2013).

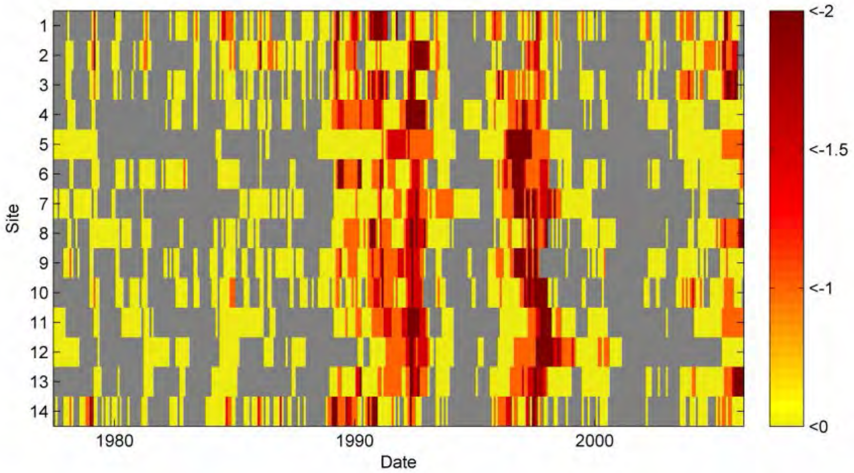

Figure 2: Heatmap of SGI < 0 for 14 groundwater level time series in Great Britain. Reproduced after Bloomfield and Marchant (2013).

Application of the SGI to two very long groundwater level time series (Chilgrove House (CH) and Dalton Holme (DH), Figure 1) has revealed changing controls on groundwater drought (Bloomfield et al., 2018). Figure 3 shows the SGI as a function of standardised temperature (STI) and precipitation (SPI) indices for the 2 sites, split over 3 time periods, with notable drought events shown in colours. In 1891-1932, 8% and 10% of groundwater drought events (SGI < -1) occurred when STI > 1 and SPI < -1 for CH and DH respectively. In contrast, in 1974-2015, the number of groundwater drought events when STI > 1 and SPI < -1 increases to 23% and 29% for CH and DH respectively, with notably greater extreme drought events SGI < -2. In the absence of long-term changes in precipitation deficits during drought events, it is inferred that increases in the incidence of monthly groundwater drought is associated with increased temperature associated with anthropogenic warming. It is postulated that this is through impacts of anthropogenic warming on evapotranspiration. Thick capillary fringes at the two sites suggest that evapotranspiration could be supported by groundwater during drought events. Given the large extent of shallow groundwater globally, this may be a significant phenomenon elsewhere (Bloomfield et al., 2018).

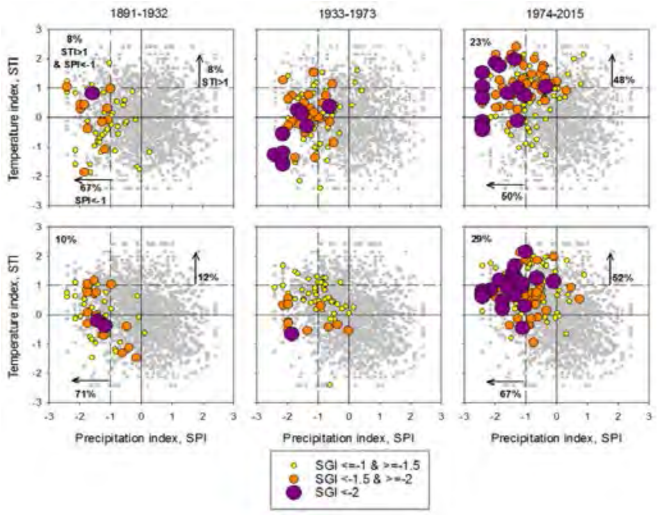

Figure 3: The SGI as a function of standardised temperature index (STI) and standardised precipitation index (SPI) for Chilgrove House (CH, top panels) and Dalton Holme (DH, bottom panels), split into 3 periods (1891-1932, 1933-1973, 1974-2015, left to right). Colours show notable drought events. Reproduced after Bloomfield et al. (2018).

LUMPED PARAMETER MODELS – RECONSTRUCTIONS AND FUTURE PREDICTIONS

Whilst there are a few rare examples of very long groundwater level time series, in general observations of groundwater levels have short durations and often have missing data. In order to reconstruct groundwater levels and infill gaps, groundwater models are required. Such models are also required for any future predictions of groundwater levels associated with seasonal forecasting or long-term climate change. The lumped parameter model AquiMod (Mackay et al., 2014) has been used extensively for these purposes. Figure 4 shows the conceptual structure of AquiMod. AquiMod has a modular structure, with modules for the soil, unsaturated and saturated zones. The soil module calculates a soil moisture balance, drainage from which is routed through the unsaturated zone to become recharge. Changes in groundwater levels are calculated based on an estimate of the aquifer storage coefficient and the mass balance between recharge entering the saturated zone and groundwater discharge calculated using aquifer permeability and discharge elevation. The model permits different structures for the saturated zone, variable time-stepping, Monte-Carlo parameter sampling for calibration and is freely available (British Geological Survey, 2019). The model is run from the command line and requires a time series of rainfall and PET as inputs, and groundwater level observations for calibration.

Figure 4 shows observed and reconstructed groundwater levels for four sites in England developed by Jackson et al. (2016) using AquiMod. Known historic drought events (e.g. 1921/22) are clearly identifiable in the reconstructed record. Operationally, the reconstructed levels are helpful as they can help contextualise current groundwater level status where observed groundwater level time series are short. The reconstructions also have benefits for longer-term strategic planning. For example, in England and Wales water companies have used yields of public water supply boreholes estimated during historic drought events for long-term water resources planning (UK Water Industry Research Ltd, 2014). The groundwater level minima calculated from the reconstructions can give an additional perspective on these yield estimates. AquiMod has also been used for seasonal forecasting groundwater levels one to three months in advance (Mackay et al., 2015) and for quantifying the impacts of climate change on groundwater levels (Prudhomme et al., 2013).

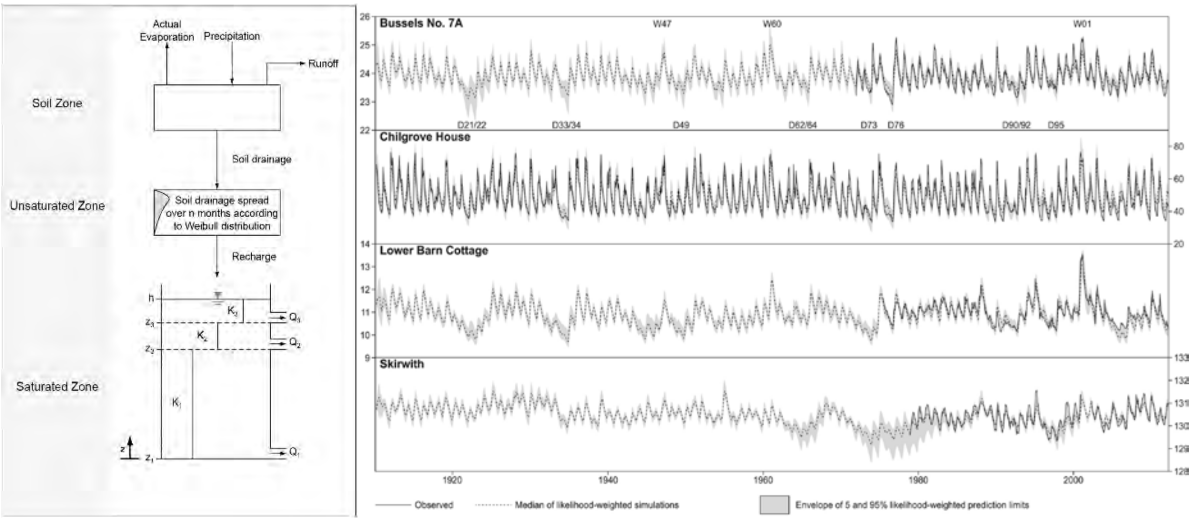

Figure 4 Conceptual structure of the AquiMod model (left) and groundwater level reconstructions produced by the model (right). Reproduced after Jackson et al. (2016) with permission from Wiley.

FROM LEVELS TO IMPACTS

The SGI and lumped parameter models such as AquiMod are useful tools for quantifying historic and future climate-driven changes in groundwater levels in observation boreholes. However, changes in levels in observation boreholes have little intrinsic value in comparison to the benefits and costs of groundwater to society. Benefits are associated with public water supply, providing baseflow to rivers and supporting wetlands, and costs associated with groundwater flooding (UK Groundwater Forum, 2018). The challenge therefore becomes how to relate changes in groundwater levels with impacts (in the examples above; public water supply yields, baseflow and ecological thresholds, groundwater flooding thresholds). In many cases, groundwater levels are one component of the controls on these impacts. In these cases, there is a need therefore to understand the interaction between the groundwater system and these other constraints to make meaningful impact predictions. A specific example of this challenge is associated with assessing the yields of public water supply boreholes under a range of future droughts.

In the UK there is a simple, well-established methodology for quantifying impacts of climate change on yields of public water supply boreholes during drought periods (UK Water Industry Research Ltd, 2014). A pumping water level-pumping rate curve during droughts (Figure 5) is developed using step-drawdown test data and operational abstraction-water level data during historic droughts. A statistical relationship between groundwater levels in a pumping borehole and an observation borehole is then used to shift the pumping water level-pumping rate curve, and yields are estimated based on the intersection of the curve and potential yield constraints (e.g. pump intake depth). However, this method doesn't account for variations in hydraulic conductivity with depth (VKD), which is well known to occur in fractured aquifers. Figure 5 shows the typical "cocktail glass" model developed by Rushton et al. (1989) of VKD in the Chalk aquifer, England. The relative significance of both changes in climate and in permeability with depth on estimates of borehole yields during droughts is poorly understood.

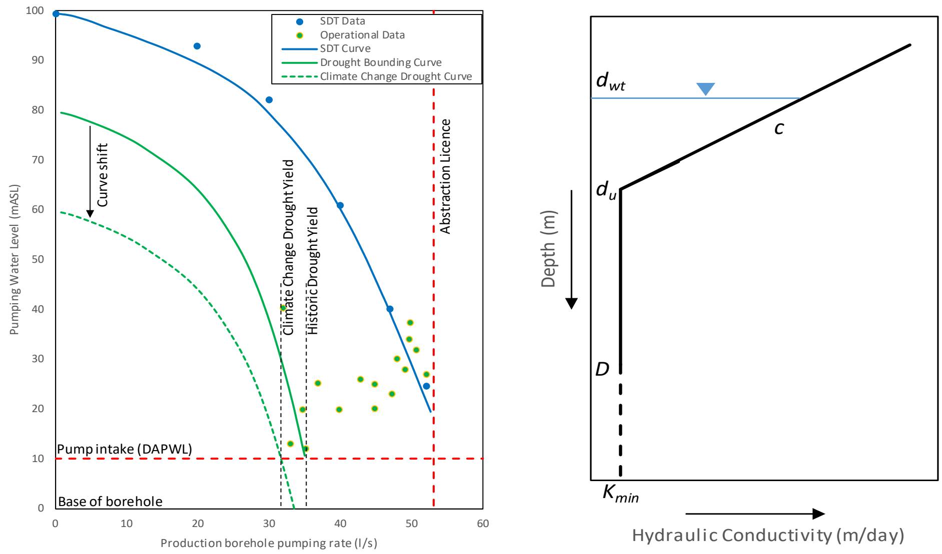

Figure 5: Yield-drawdown plot for estimating borehole yields under historic and future conditions (left) and the "cocktail glass" model of VKD (right). Adapted after Foster and Sage (2017) with permission of Springer and Rushton et al. (1989) with permission from the Geological Society of London.

To address this, Ascott et al. (2019) developed a simple radial groundwater flow model of a conceptual site around a pumping borehole. Six abstraction rates, 11 different VKD profiles and 20 different climate scenarios were implemented, resulting in 1320 model runs. For each run, the relative significance of climate and VKD profile on groundwater levels and yield estimates during drought periods was evaluated. Figure 6 shows the drawdown response as a function of the mean permeability of each profile and annual recharge for each climate scenario, for the 1976 drought event. Across all abstraction rates and drought years, VKD is more significant ($P < 0.001$) than with climate change in controlling lowest pumping water levels ($P > 0.1$). Both VKD and climate are significant controls on borehole yields, but responses are non-linear due to pumping water level-pumping rate curves intersecting yield constraints (Figure 5).

Whilst the SGI and AquiMod have been used extensively in research applications, to date operational use of these tools in practice has been limited. In recent years there has been a significant development of high performance computing facilities. In parallel with this, environmental regulators are increasingly adopting policies for open access to datasets in real-time (Environment Agency, 2019). These trends open up the possibility of automating the SGI and AquiMod to be run in real-time using live groundwater level data. Such "real-time services" have been already been developed for surface water (Environment Agency, 2019), but limited work to date has developed these for groundwater.

CONCLUSIONS

In this paper, we review methods and models for quantifying climate-driven changes in groundwater resources. The SGI and AquiMod are shown to be powerful tools for quantifying historic and future changes in groundwater levels. However, there remain significant challenges in in relating changes in groundwater levels to impacts across different sectors (e.g. yields of public water supply boreholes). Future research should: (1) explore the full extent of the SGI, rather than just drought, (2) apply the latest climate model data to AquiMod models and (3) develop improved links between observation borehole groundwater levels and impacts. Use of live open access datasets and high performance computing facilities will allow the methods and models presented here to be applied as a real-time service.

ACKNOWLEDGEMENTS

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APPROACHES TO ESTIMATING THE IMPACTS OF CLIMATE CHANGE ON GROUNDWATER RECHARGE TO IRISH BEDROCK AQUIFERS

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ABSTRACT

Local and regional hydrogeological features have a strong influence on the potential impacts of a changing climate on groundwater recharge. In Ireland, where approximately 70% of the country is underlain by aquifers that are regarded as poorly productive, the aquifer's storage availability has been found to be the main constraining factor on groundwater recharge. A recharge characterisation exercise has been carried out for two study areas to examine recharge uncertainty and use it as a proxy to assess the specific yield. The methods used include: water table fluctuation analysis, the NAM rainfall-runoff model and river baseflow separation. Furthermore, to be able to represent water level behaviour under future climate conditions, a method combining wavelet transform analysis and neural network forecasting has been applied. First, the maximum overlap discrete wavelet transforms (MODWT) are used to decompose the input signals, which are then fed into the neural networks. In this case, nonlinear autoregressive neural networks (NARX) have been used as they predict a variable based on exogenous input signals (rainfall, temperature) and regressed values of the output signal (groundwater level).Once the networks are trained and validated, the model can then be forced with climate projections or modified meteorological series to explore the effects of climate variability, while considering the hydrogeological characteristics of the study area.

INTRODUCTION

Groundwater recharge rates may be limited by the aquifer storage capacity (Scanlon et al. 2002). Additionally, the amount of recharge is also determined by subsoil characteristics including their thickness and permeability (Hulme et al. 2001). Both the subsoil characteristics and the aquifer storage capacity are especially relevant in the Irish context. Firstly, because a significant part of the island is covered by glacial deposits, generally between 5-15 m in thickness, which can impede downward percolation of potential recharge water (Fitzsimons and Misstear 2006). Secondly, because approximately 70% of the country is underlain by hard-rock geological formations considered to be 'poorly productive aquifers' (Williams and Lee 2010) . An initial sensitivity analysis using the national recharge map (Hunter Williams et al. 2013) showed that the aquifer storage capacity is indeed the main controlling factor on recharge in Irish fractured aquifers, followed by the infiltration capacity and then the hydrometeorological variables.

Climate variability is expected to affect the hydrological cycle by intensifying it. Climate change impact assessment studies have mainly focused on surface water due to its visibility and the clear flooding risks involved. The IPCC fourth and fifth reports (IPCC 2007; IPCC et al. 2013) provide a good outline of how the impact assessment studies on groundwater have evolved in the last decade. Even though the number of studies increased significantly between the two reports, most of the studies have been at the local scale (IPCC et al. 2013).

This research is part of a PhD project, the main aim of which is to improve our understanding on groundwater recharge processes in the Irish context and how groundwater resources may be impacted by climate change. This paper outlines some of the relevant research carried out during this project. Firstly, a recharge characterisation is presented to illustrate how hydrogeological features control groundwater recharge. Secondly, a novel approach is described for making forecasts of groundwater levels while considering the findings from the recharge characterisation. State of the art methods such as wavelet transforms and artificial neural networks are used for this purpose. Finally, two different methodologies to assess the possible impacts of climate change on groundwater resources are presented.

STUDY AREAS

Two Irish catchments with contrasting hydrogeological and climate properties have been selected for this project: Mattock (Co. Louth), and Dripsey (Co. Cork). These catchments were selected based on data availability (river discharge and groundwater levels), as well as information from previous studies.

The bedrock geology of the Mattock Catchment mainly comprises Ordovician volcanics. These materials constitute a single aquifer type, regarded as "Poor" which has a corresponding recharge cap of 100 mm/y. In contrast, the Dripsey is underlain by Devonian Old Red Sandstones. The ORS is classified as "Locally Important" and has an associated recharge cap of 200 mm/y. The main characteristics of the study areas are summarised in Table1.

Table 1: Characteristics of the selected catchments. The annual values presented are the averages for the period 1985 to 2015

	Mattock	**Dripsey**
Area (km^2)	16	82
Underlying Aquifer	Poor Aquifer	Locally Important Aquifer
Recharge Caps	100 mm/y	200 mm/y
Main land use	Pasture	Pasture
Vulnerability Category	Extreme to Low	Extreme to Moderate
Precipitation (mm/y)	970	1227
PE(mm/y)	544	514
AE (mm/y)	493	465
Effective rainfall (mm/y)	478	761

AQUIFER STORAGE CAPACITY ESTIMATION: RECHARGE CHARACTERISATION

Because the storage capacity of the aquifers cannot be measured directly, a recharge characterisation exercise has been carried out for these two contrasting study catchments.

WATER TABLE FLUCTUATION METHOD

For this study, the methodology presented by Crosbie et al. (2005) has been applied with some modifications to adapt it to the local hydrogeology. This technique was chosen because it is based on a continuous time series approach rather than an event-based one. Secondly, this methodology had already been applied in Ireland (Cai and Ofterdinger 2016). The model presented by Crosbie et al. (2005) is described by equation (1):

$$R_t = \begin{cases} [(h_t - h_{t-1}) + D(z)\Delta t]S_{ya} \; if \begin{cases} [(h_t - h_{t-1}) + D(z)\Delta t] > 0 \\ \sum_{t>t'>t-\propto} P_{t'} > 0 \\ h_t < h_{t+\beta} + D(z)\Delta t \end{cases} \\ 0 \; otherwise \end{cases} \tag{1}$$

where R_t is recharge at time t, h_t is water level at time t, $D(z)$ is the drainage rate, S_{ya} is the apparent specific yield, P_t is precipitation at time t, α is a precipitation time parameter and β is the Lisse effect parameter.

Equation 1 shows that groundwater recharge can be calculated by multiplying the water table increment by the apparent specific yield (adjusted at each time step) where the difference between the drainage term and the water level rise is greater than 0. It also accounts for the response time of the aquifer (α) and the Lisse effect that can take place in shallow aquifers after intense rain events.

Three main modifications were made from the original method: 1) constant S_y values have been used rather than apparent S_y due to the uncertainty of this parameter in fractured bedrock aquifers; 2) instead of fitting a linear trend to calculate the drainage term as a function of the water table level, the mean value for each class has been taken; and 3) the Lisse effect has been neglected due to the depth of the observation boreholes, since it is considered to occur only in areas where the unsaturated zone is thinner than 1-1.3m. Moreover, this effect is more common in porous aquifers, even though it can also take place in micro-fractures.

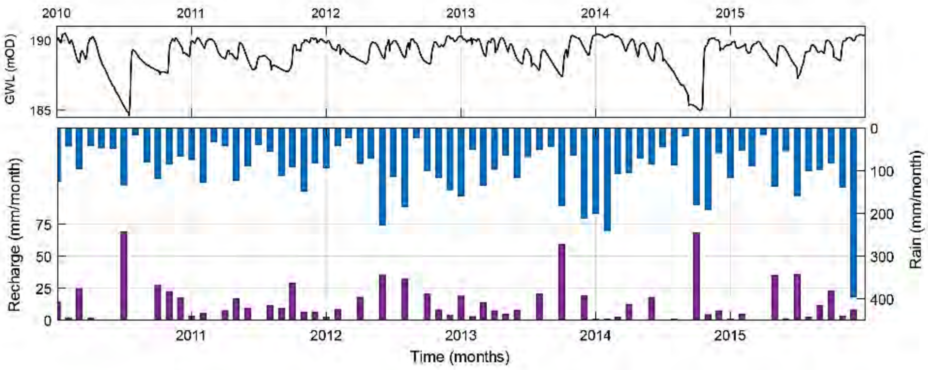

Figure 1: Top: observed groundwater level time series. Bottom: monthly rainfall (blue, right-hand Y axis) and calculated monthly recharge (purple, left-hand Y axis) for the DR1-shallow monitoring point in the Dripsey, assuming a S_y of 0.02.

Figure 1 shows the monthly recharge values calculated for the Dripsey. At first sight, the results appear to be illogical since the same amount of rainfall generates different recharge responses for some months. To understand this behaviour, recharge estimations need to be compared with the water table levels. By doing this, it becomes clear that most of these events are linked to high water table levels, suggesting that the aquifer is unable to accept further recharge. The results obtained for the Mattock catchment show a similar behaviour.

BASEFLOW SEPARATION

River hydrograph analysis can provide valuable insights on groundwater recharge. The river hydrograph represents the total of the overland flow, interflow and groundwater flow or baseflow. When this method is applied to annual or multiannual time series, it can be used as a proxy for groundwater recharge by the principle of conservation of mass. In this case, the Eckhardt recursive digital filter (Eckhardt 2005) was implemented according to the equation:

$$B_{k+1} = \frac{(1 - BFI_{max}) \cdot \alpha \cdot B_k + (1 - \alpha) \cdot BFI_{max} \cdot Q_{k+1}}{1 - \alpha \cdot BFI_{max}} \qquad (2)$$

where α is the baseflow filter parameter (0.98 by default) and BFI_{max} represents the maximum value of long-term base-flow index (BFI). The α parameter can be adjusted by a recession analysis. Eckhardt (2005) also proposed predefined values of BFI_{max} depending on the hydrogeological settings; a value of 0.25 is suggested for perennial streams within hard-rock aquifers, so was taken as the initial value here. However, given that this value controls the maximum baseflow percentage, it was investigated to determine an optimal value, based on previous knowledge of the catchments.

Table 2 summarises the results obtained for the two catchments. The evaluation of the BFI_{max} parameter leads to similar results for both catchments. In the case of the Mattock the results can be compared to previous studies where other baseflow separation methods were applied. For instance, results from chemical separation methods for different flow states in the EPA Pathways project report (Archbold et al. 2013) show that the contributions during January and February 2012 were 27%, reducing to 20% during the month of June 2012. These baseflow estimations indicate that the most appropriate BFI_{max} value to use is 0.20, which gives a BFI for the Mattock catchment of 21-23%, with a recharge of 139 to 170 mm/y.

Even though the Dripsey catchment was studied previously for nutrient transport purposes and flooding assessment (Kiely et al. 2008), just the area next to the outlet (15km^2) was considered for baseflow analyses rather than the whole catchment (82km^2), and therefore the BFI estimations are not directly comparable to those obtained with the Eckhardt filter here (Table 2). A report by Moe et al. (2010) on the physical characteristics of the catchment and its conceptual model shows that the Dripsey presents a well-developed transition zone, which is regarded as the main flow pathway. In light of the conceptual model and also comparing with the results obtained from the Water Table Fluctuation Method, the results obtained with the BFI_{max} value of 30 seem the most reasonable, which would correspond to BFI of 32-34% and annual recharge values between 209 and 256 mm/year.

Table 2: Annual baseflow estimation and corresponding baseflow index (BFI) estimated from the evaluation of the BFI_{max} parameter for the two study catchments.

	Dripsey						Mattock					
	BFI_{max} 20		BFI_{max} 25		BFI_{max} 30		BFI_{max} 20		BFI_{max} 25		BFI_{max} 30	
	BF	BFI	BF	BFI	BF	BFI	BF	BFI	BF	BFI	BF	BFI
2012	139	0.22	174	0.27	210	0.32	139	0.22	176	0.27	211	0.32
2013	139	0.23	174	0.28	209	0.34	139	0.22	175	0.28	210	0.33
2014	171	0.24	213	0.29	256	0.34	170	0.23	211	0.29	253	0.34
2015	156	0.22	196	0.27	236	0.32	157	0.21	201	0.27	243	0.32

RAINFALL-RUNOFF MODELLING

The “Nedbor-Afstromnings-Model” or NAM is a deterministic, lumped and conceptual rainfall-runoff model (Nielsen and Hansen 1973) that is integrated as a module of the MIKE11 river modelling package. This model simulates the different variables of the water cycle using rainfall and potential evapotranspiration as inputs. The model includes a sequence of four reservoirs that represent snow storage, surface storage, root zone storage and groundwater storage. Additionally, the baseflow component can be subdivided into shallow and deep to reproduce the faster and slower groundwater responses. The resulting runoff is separated into overland flow, from soil moisture excess in the surface storage, interflow from the second storage, and finally the baseflow from the deep storage (O’Brien et al. 2013).

The NAM model was implemented in the Dripsey catchment for the same 2010-2015 period as the methods described above. The results suggest that the average BFI is about 30%, with a clear dominance of shallow groundwater flow (24.8%) and a much smaller contribution from the deep groundwater flow (6.5%). In the Mattock, due to its reduced catchment size, higher resolution rainfall data were required. The calibration was carried out for the 2011-2012 period with 15-minute data. The results suggest a baseflow index of 17% with 10% coming from shallow groundwater and 7% from deeper groundwater flow.

The overall results suggest that groundwater recharge ranges between 200-270 mm/y for the Dripsey catchment and 52-140 mm/y for the Mattock catchment. However, these results must be treated with caution, remembering that each method measures slightly different things and all methods have their limitations. Nevertheless, the range of likely recharge values obtained has been used to obtain the corresponding S_y range by inverting the water table fluctuation equation. In this way, the S_y has been estimated as 0.02-0.04 for the Dripsey catchment and 0.01-0.03 for the Mattock catchment, which are regarded as reasonable values for these two aquifer types.

GROUNDWATER LEVELS FORECAST: WT-NARX COUPLING

As has been shown by the recharge characterisation, and especially the water table fluctuation method, the aquifer storage capacity plays an important role in determining the amount of groundwater recharge. In this section, a new approach is described to take account of the local hydrogeological features under future conditions, as summarised below.

MAXIMUM OVERLAP DISCRETE WAVELET TRANSFORMS (MODWT)

Wavelet transforms are powerful mathematical tools, mainly used to provide a full time-scale representation of transient phenomena occurring at different time scales (Labat et al. 2000). They can be defined as rapidly decaying wave-like oscillations with a mean value of 0 (Valens 1999). These oscillations are based on mathematical functions (mother wavelets) that can be translated through the signal (by shifting) and compacted or elongated (by scaling) to achieve the complete representation of the signal. Discrete Wavelet Transforms (DWT) are useful to decompose time-series into orthogonal details with a specific range of frequencies and hence to perform multi-resolution analysis. However, DWTs can only be performed on time-series of dyadic length, that is, if their length is a power of two. Maximum Overlap Discrete Wavelet Transforms (MODWT) are a variant of DWT that can be applied similarly for multi-resolution analysis, with the advantage that they can handle any sample length. In addition, even though the MODWT decomposition is not orthonormal and therefore more redundant, it is more efficient than DWT because it preserves the energy in the signal and avoids border effects. In this project, the MODWT has been applied to decompose the predictor time-series (mean temperature, rainfall and PE) into details that are then used to feed the NARX model to forecast groundwater levels. In order to minimize the number of input features, the decomposed time-series have been grouped into physically-meaningful sets.

NONLINEAR AUTOREGRESSIVE NEURAL NETWORKS (NARX)

In recent years, there has been a rise in the use of machine-learning techniques in surface hydrology and, more recently, in hydrogeology. Data-driven modelling is an area of rapid development that has led to its application to the forecast of groundwater levels (e.g: Adamowski and Chan 2011; Wunsch et al. 2018). Whereas physically-based models are based on the understanding of the physical processes occurring within the study area, data-driven models are “black-box models” whose purpose is to find a relationship between inputs and outputs. Hence, while the physically-based models can become extremely complex, they are often unable to represent the spatial variation of the physical properties and stochasticity of the hydrological processes. In contrast, data-driven models can provide a representation of these processes, but they lack physical meaning, and do not have parameters that can be adjusted based on expertise. The most common method for data-driven models is the artificial neural networks (ANN) and, particularly, the multi-layer-perceptron (MLP). These networks are composed of several layers that transmit the information forward solely. However, when the system being modelled presents a high autocorrelation, as in the case of groundwater levels, this characteristic is a disadvantage. For this reason, Nonlinear Autoregressive Networks with Exogenous inputs (NARX) have been used instead. NARX is a recurrent dynamic network based on the ARX linear model, that coupled with ANN, enables the simulation of nonlinearities. Therefore, the main characteristic of the NARX models is the back-propagation of the outputs at each timestep, so it informs the network for the forecast of the following time step (closed loop configuration). Nevertheless, the model can be trained as a simple feed-forward network in order to simplify the process (open loop configuration) and close the system when multi-step forecasts are required. The NARX model has been implemented using the Neural Network Toolbox™ integrated in MATLAB®. There are three main parameters to configure the architecture of the NARX model before training it: Input Delays (ID), Feedback Delays (FD) and Number of Hidden Nodes (HD). The ID can be approximated by identifying the significant lags between the predictors and the predictand.

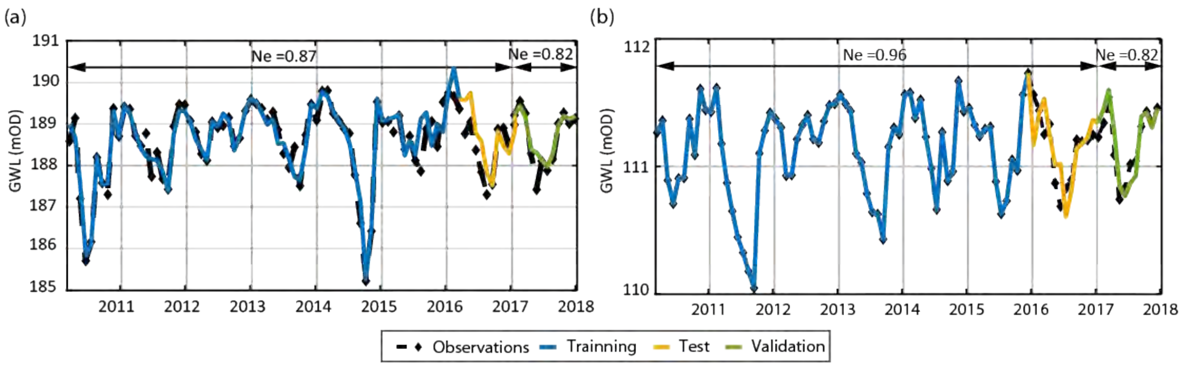

Figure 2: Comparison of the observed groundwater levels (black line), and the simulated levels during the training (blue), test (yellow) and validation (green) periods for (a) Dripsey and (b) Mattock.

Similarly, the FD can be identified performing the lagged autocorrelation of the groundwater levels. However, there is no formal way to determine the optimal number of hidden layers that a NARX model should have, and this must be assessed by trial and error.

Once the NARX architecture is defined, the model can be trained. Firstly, the dataset is divided into three blocks: training, testing and validation. In this case, six years of the dataset have been used for training, one for testing and one for validation. As the testing is carried out automatically with the training, it is important to leave the validation dataset out of the process to ensure an unbiased estimation of the model performance. The training of the model was carried out with the Bayesian regularisation backpropagation algorithm (based on the Levenberg-Marquardt optimisation) to ensure a good generalisation of the NN (MacKay and Systems 1992). Several combinations of inputs have been tested in this project.

Figure 2 shows the performance of the best combination found for each of the study areas. In the case of the Mattock catchment, the overall performance is 0.96 during the training period and 0.82 during the validation, according to the Nash-Sutcliffe efficiency. Likewise, the performance achieved for the Dripsey catchment is 0.87 for the training and testing periods, and 0.82 for the validation period.

GENERATING FUTURE SCENARIOS

The possible impacts of a changing climate on groundwater resources have been traditionally simulated by forcing hydrologic models with climate projections. Even though there is a rising awareness about the limitations of climate projections, they have become the default tool to generate future hydrogeologic scenarios (Holman et al. 2012). As has been acknowledged by some authors, the main limitation arises from the fact that climate models were initially designed to provide an assessment of the global climate under specific greenhouse conditions, but not to provide the level of accuracy required for local impact and adaptation assessments (Wilby 2005; Kundzewicz and Stakhiv 2010). For this reason, two different approaches have been applied in the current research to estimate the groundwater resources under future climate scenarios. The first approach involves forcing the NAM model with climate projections provided by Met Eireann-ICHEC. In this way, future scenarios of baseflow have been generated with five different models, and two different representative concentration pathways, adding up to a total of 10 future hydrologic scenarios. However, when interpreting the results, it must be kept in mind that the purpose of the climate models is not to forecast specific events but to provide a statistical characterisation of the climate variability. Hence, the results must be interpreted only as a general characterisation of the system. However, it is possible to establish seasonal changes and patterns as well as inter-annual changes and average values of the variables of interest.

The second approach consists of using a stochastic weather generator to modify the time-series of observations over the catchments. Synthetic years with modified rainfall, temperature seasonality, and extreme values are generated which then feed the NARX model and forecast the resulting groundwater levels. This second approach allows the assessment of the system's sensitivity to specific changes in relevant meteorological variables and consequently, to identify critical values for the system.

INTERIM CONCLUSIONS

The research outlined in this paper involves: (i) determining how aquifer properties control groundwater recharge; (ii) implementing novel methodologies that allow the simulation of groundwater levels under future climate scenarios, while accounting for the local hydrogeological characteristics and (iii) generating more accurate assessments of the impacts of climate variability on groundwater recharge.

The recharge characterisation has been used to constrain recharge uncertainty and use it as a proxy to assess the specific yield in fractured aquifers. Then, a coupled wavelet transform-neural network methodology has been applied to explore the effects of climate variability while considering the specific hydrogeological characteristics of the study areas. The results show that this method can reproduce the water table dynamics effectively and hence is a suitable technique to simulate water level variations under a changing climate. Finally, two different approaches are being used to assess the impacts of climate change on groundwater recharge: a classical approach, forcing a rainfall-runoff model with climate projections to provide long term simulations and significant ranges of change; and a second approach involving a stochastically-modified meteorological time-series that is fed into the NARX model to determine the sensitivity of the system and identify critical values.

AKNOWLEDGEMENTS

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SESSION II

FLOW AND CONTAMINANT TRANSPORT MODELLING ON AN IRISH KARST SYSTEM

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ABSTRACT

We modelled flow and contaminant transport on a small Irish catchment located in county Leitrim, Ireland. This karst system feeds the Manorhamilton spring through a well-developed network of conduits. Several tracer tests were carried out from different sinkholes on the catchment to the main spring. We used Modflow with the UnStructured Grid (USG) and Connected Linear Networks (CLN) modules developed by USGS (Panday et al., 2013). We first built a 3D geological model (using MOVE, Midland Valley-Petex) to characterise precisely the aquifer, before simulating flow using Modflow, calibrating against the measured spring discharge. We then modelled punctual contaminant transport using a tracer test to calibrate relevant parameters. This fully distributed approach enables flow and conservative contaminant transport to be simulated simultaneously in a multi-porosity aquifer. Whilst it does require a good understanding a the system, large datasets and a relatively long calibration process, it provides a powerful tool which can be used to further understand the dynamics of the karst aquifer involved and can help inform the management of water resources both quantitatively and qualitatively.

USING MULTI-LEVEL PIEZOMETRY TO DETERMINE VERTICAL STRATIGRAPHIC VARIATIONS IN SALINE AQUIFERS, MALAWI.

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ABSTRACT

This research is concerned with aquifer units that are separated by an aquitard/ aquiclude, in areas affected by salinity. Hydraulic parameters and geochemistry are analysed for vertical variations between the aquifer units. Connectivity of units is studied, and vertical flow gradients determined. This is to study if the salinity is from a specific unit and hence could be blocked, or if the aquifer units are hydraulically connected. This is a step forward along the complex path to determining a salinity source, which is necessary as dependence on groundwater increases with population growth and climate change.

An in-depth desk study was conducted to locate suitable abandoned saline boreholes. A borehole camera survey determined which of these had two slotted casings, assuming slotted casings correspond to aquifer units. Piezometer installations were designed from the camera survey. Step-tests were carried out, and chemistry samples taken before piezometer installation. Slug tests were conducted, and chemistry and isotope samples taken from both levels of the piezometer.

Two sites, Manjolo and Kampomo, show no vertical variations and strong aquifer connectivity. Through critiquing conceptual models, it is likely there is a gravel pack providing hydraulic connection, hence it is not possible to determine if the salinity is confined to one unit. The third site, Chabwedzeka, shows some vertical variations and limited connectivity. Through critiquing models, salinity does not appear to be confined to one unit. A major limiting factor is the lack of knowledge on borehole configuration. There are several limitations, recommendations have been made based on this.

INVESTIGATION OF ANTICOCCIDIAL DRUG OCCURRENCE IN IRISH KARST AND FRACTURED AQUIFERS: PRELIMINARY FINDINGS

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ABSTRACT

Anticoccidials are used to control coccidiosis and other protozoan infections in food producing animals. They are licensed in the EU both as veterinary drugs for therapeutic treatment and/ or as feed additives, with primary prophylactic use in poultry production (and to a lesser extent in pigs, calves and lambs). Excretion in manure and subsequent landspreading provides a potential pathway to groundwater, so these substances are considered to be emerging organic contaminants of concern. The aim of this work was to develop a comprehensive method for the determination of commonly used anticoccidials in environmental water samples, in order to investigate the occurrence of these contaminants in an Irish groundwater setting. A multi-residue method based on Solid Phase Extraction (SPE) with Ultra High Performance Liquid Chromatography Tandem Mass Spectrometry (UHPLC-MS/MS) detection was developed for the determination of 28 anticoccidials in water. This method was applied in a comprehensive spatial study whereby 107 samples (61 borehole and 46 spring samples), representative of the different karst and fractured aquifer categories in Ireland, were sampled and analysed during November 2018. The preliminary findings of this study are presented here, which show detections of up to 7 different anticoccidial compounds at 23 % of sites sampled (25 of 107).

[Keywords: agro-chemical, anticoccidials, emerging organic contaminant, groundwater, karst]

REVEALING SHALLOW GROUNDWATER PATHWAYS TO HEADWATER STREAM NETWORKS IN FRACTURED BEDROCK ENVIRONMENTS

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ABSTRACT

Over two thirds of the Island of Ireland is underlain by thin fractured bedrock aquifers which are often highly vulnerable to pollution. These aquifers are a vital source of baseflow to stream networks in dry weather but are the least understood flow regime. The goal of the present study is to better understand pathways of groundwater discharge to surface water in a representative fractured bedrock catchment in Co. Cork. A high-resolution streambed temperature and specific electrical conductance survey was carried out over a 400 m stream reach. A novel roaming temperature probe capable of recording GPS location and point temperature profiles at three depths (0, 10 and 20 cm below bed level) simultaneously was designed and built for the project. Relative stream flow accretion/depletion was investigated using two-point tracer dilution gauging. Near-surface geology was characterised using 2D electrical resistivity tomography (ERT). Temperature mapping results indicate that groundwater discharge is concentrated through small-scale preferential pathways in the streambed. These thermal anomalies were associated with vertical features observed in bank-side ERT profiles suggesting that streambed pathways are linked to deeper structural controls in the bedrock. Our findings also suggest that artificial deepening of drainage networks may locally enhance groundwater-surface water connectivity.

GROUNDWATER CONTAMINATION WITH ANTIBIOTIC RESISTANT BACTERIA: A SYSTEMATIC REVIEW OF INCIDENCE, FREQUENCY AND TEMPORAL TENDENCIES

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ABSTRACT

Groundwater is the most extracted raw material worldwide and, one of the least understood components of the water cycle. Thus, managing contamination threats to the subsurface is inherently challenging. Compounding this, groundwater supplies are potential reservoirs for antibiotic resistance (AR), perhaps the most significant current threat to global health. AR is a natural occurrence, however anthropogenic pressures are rapidly shifting its ecology in the environment, leading to dangerously high levels of AR infections. In that context, high residence times and low transmissivity in the subsurface can result in highly stable condition for AR to occur, thus enabling horizontal transfer of AR genes and proliferation of antibiotic resistant bacteria (ARB). Despite this, no comprehensive synthesis of ARB incidence in groundwater environments has been undertaken to date. Accordingly, a systematic review of international literature was carried out, with seventy relevant studies identified, comprising 8,160 groundwater samples. In all, 70% of studied groundwater systems (n=49) were classified as high-risk environmental sources of ARB, of which 93.9% were used for human consumption (n=46). This confirms the significance of groundwater sources as ARB reservoirs and human exposure routes. Moreover, it emphasises a clear need for groundwater-focused interventions to reduce environmental and human exposure to AR.

RESOLVING THE HISTORY OF BURIED KARST BETWEEN LOUGH CORRIB AND GALWAY CITY

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ABSTRACT

The discovery of a previously unknown c.100 m deep sediment-filled karst feature in the area between Lough Corrib and Galway city (during preliminary site investigation for the N6 Galway City outer bypass road) has prompted a research project focused on improving the understanding of both the local hydrogeology and regional geology. A detailed geological investigation of the unconsolidated infill sediment and local limestone bedrock in the vicinity of the large-scale karst depression provides insight into the timing of formation as well as the founding hydrological and hydrogeological processes. The east-west trend in the development of the deep enclosed depression is a function of the structural geology. A fault, striking roughly east-west, aligns with the long axis of the karst feature and with a deep conduit which ostensibly connects to the karst feature. This fault continues to channel groundwater today whilst major joint sets developed in the limestone also appear to exert control on the movement of groundwater. Rotated limestone slabs and sediment laminae provide evidence for a collapse event presumably into an enlarged section of the deep, fault controlled conduit. Fluvial and lacustrine palaeoenvironments are interpreted from the infill sediment. The presence of certain pollen species and overall specie assemblages within the organic clays suggest deposition within the karst depression occurred from as far back as the Late Pleistocene or older, giving a minimum age for the karst feature.

HYDROLOGY AND HYDROCHEMISTRY IN IRISH CALCEREOUS FENS

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ABSTRACT

Alkaline and Cladium fens are protected under the European Union (EU) Habitats Directive (Council Directive 92/43/EEC) as Special Areas of Conservation (SAC). These fens are peat-forming wetlands predominantly fed by groundwater containing significant concentrations of calcium, magnesium and bicarbonate. The hydrogeological dynamics and hydro-chemical signature supports small sedge and brown moss communities in a mosaic of different habitats. Little is known about the hydrology and hydrochemistry that support fen habitat than for other GWDTE's (Groundwater Dependent Terrestrial Ecosystems) such as bogs and turloughs. As part of a three year EPA funded research project (Ecometrics) on GWDTE's, this research aims to quantify the eco-hydrological and groundwater linkage for calcareous fens in Ireland. Four fen sites covering an eco-hydrological gradient from pristine to highly degraded conditions were selected for the study. Each site is instrumented with a habitat and catchment hydrometric monitoring network. Since July 2018, hydro-chemical data is collected by sampling and analysing ground and surface waters for nutrients, minerals and metals. These data is currently being collated in order to define appropriate metrics that characterise the environmental supporting conditions in fens as required for the EU Water Framework Directive. This poster will present preliminary data from the investigation.

Keywords: GWDTEs, SAC, peat, fen, hydrology, hydrochemistry, nutrients

ASSESSING THE POTENTIAL FOR NATURAL FLOOD MANAGEMENT (NFM) IN THE UPPER LEE CATCHMENT, IRELAND

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ABSTRACT

Traditional flood risk management policy in Ireland has focused on structural measures to protect, control and defend against flooding. Embankments, walls and flow control structures focus on a single point within the catchment, where a cost benefit analysis dictates their viability. Such defences have proven successful, albeit costly, but questions are now being raised about their sustainability with climate change. While such measures work well in large urban areas, upper catchment rural villages are often deemed uneconomical to protect with structural measures.

Natural Flood Management (NFM) is the alteration, restoration or use of landscape features to reduce flood risk. NFM projects have been implemented in the UK, most notably in the Belford Catchment, Northumberland, with considerable success. To date, no such schemes have been implemented in Ireland. NFM has the potential to offer flood risk management to upper catchment communities deemed uneconomical to protect with traditional hard engineering approaches. Stakeholder engagement identified Ballingeary, Co. Cork as a suitable demonstration catchment. Scenario analysis was utilised to identify a pragmatic delivery route to implement an NFM scheme for the village. Results of the study suggest that a partnership between the OPW and a local flood committee, with funding from the OPW Minor Works budget offers the greatest certainty of long term success. The study indicates that funding; access to private lands; landowner participation; and maintenance are the main barriers to NFM in Ireland. A series of sediment traps; ponds; and woody debris were designed and modelled using Arc Hydro to understand their performance. Materials chosen for the design are locally sourced and sustainable, with their constructability centred on the capabilities of the local community. Each feature is designed to be adaptable to climate change. Co-benefits include sediment trapping to improve water quality; increasing biodiversity; and promoting aquifer recharge.

FROM BEDROCK TO DESKTOP: IMPROVING THE GROUNDWATER GEOCHEMISTRY TOOLKIT FOR MINERAL EXPLORATION

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ABSTRACT

Geochemical sampling (rock, soil and water) is one of the most valuable techniques employed by the mineral exploration industry to find new deposits. Assessing groundwater chemistry is particularly useful for vectoring towards potential mineralisation; properly contextualised groundwater data can provide insight into flow patterns and controls, the age of the water and the lithologies it has moved through. Better sampling techniques (e.g. U.S. E.P.A., 1996) and recent advances in approaches to the statistical analysis of geochemistry data (e.g. Aitchison, 1994 and Blake et al., 2016) have allowed for a more comprehensive understanding of water/rock interactions in the subsurface. With this in mind it may be prudent to produce a procedure that can be followed, allowing for the greatest dividend from groundwater sampling in the context of mineral exploration and groundwater management. This procedure would include best practice for the collection and analysis of groundwater samples as well as a description of how to get the most out of the subsequent data using advanced statistics and mapping techniques. Presented here is an example of a potential procedure using groundwater geochemistry data from Lisheen, Co. Tipperary, a known carbonate-hosted massive sulphide lead/zinc deposit, to demonstrate the value of the methods employed.

A NEW METHODOLOGY FOR PROVIDING GEOLOGICAL CONSTRAINTS ON SPATIAL VARIATIONS IN GROUNDWATER FLOW POTENTIAL, AS DEMONSTRATED IN THE FRACTURED BEDROCKS OF IRELAND.

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ABSTRACT

Mapping groundwater flow at regional scales is generally considered to be an important aspect of conceptualising flow for a particular site or area. In the hydrogeological literature a number of different mapping methods have been applied and are largely determined by data availability. Typically these rely on the definition of regional trends integrating a variety of factors including lithological through to structural. In this study we consider the practical challenges of defining regional trends for groundwater flow in fracture systems. We suggest that the principal limitations of existing methods arises from the difficulty of defining representative flow properties within fracture systems and the often limited value attached to mapping the nature and configuration of different types of geological structures within a particular site or area.

In central Ireland, where flow within Carboniferous bedrock dominantly occurs via faults, fractures and karst, the national bedrock aquifer map has been created by grouping bedrock formations based on flow response. These changes in flow response are related to differences in the nature and persistence of structures through sequences with characteristic mechanical stratigraphy. Whilst the main fault/fracture types show broad changes in geometry and intensity across Ireland, geometric and hydraulic heterogeneity on a local scale are the pre-eminent controls on groundwater systems for particular sites or areas. This places greater emphasis on the mapping of geological structures within an area as a prelude to understanding or predicting associated fluid flow. In this poster we describe a general methodology for considering the impact of geology on groundwater flow that incorporates three fundamental geological controls: lithological, structural and spatial. This approach combines generic insights on lithological and structural controls on groundwater flow, with an appreciation of the very strong flow heterogeneities associated with fracture/fault and karst systems at the scale of a given site or study area.

SESSION III

IRISH DROUGHT: PAST AND FUTURE PERSPECTIVES

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ABSTRACT

This paper provides an overview of work conducted on development of an historical drought catalogue for the island of Ireland, together with recently completed and ongoing work on examining past and future droughts. Each section provides an overview of key results and discussion points. Where available we point to published papers where the interested reader can gain further detail. We conclude by outlining ongoing work.

THE ISLAND OF IRELAND PRECIPITATION (IIP) NETWORK

Long-term quality assured rainfall records are critical for understanding hydro-climatic variability and change. Such records are critical for underpinning the identification and analysis of historical droughts. For Ireland, Noone et al. (2016) developed a long-term quality assured monthly precipitation network of 25 stations across the island of Ireland. The dataset was quality assured, homogenised and extended to a common start year of 1850 using station meta-data and the homogenisation tool HOMER (Noone et al., 2016). The work also derived an island of Ireland composite series comprising the mean of each of the 25 series. Figure 1 shows the distribution of gauges in IIP network. The data are available via the Met Eireann website https://www.met.ie/climate/available-data/long-term-data-sets

A DROUGHT CATLALOGUE FOR THE ISLAND OF IRELAND 1850-PRESENT

Using the IIP network and composite series Noone et al. (2017) used the Standardised Precipitation Index (SPI) to identify historical drought events. SPI-12 (12 month accumulations) was used to identify droughts given the importance of SPI-12 to water management and the propagation of impacts across different sectors. Newspaper records were employed to both verify droughts from the early record and to shed light on the socio-economic impacts of past events. In Ireland newspaper records are a rich documentary source with some of the longest running continuous publication in the world available (e.g. Belfast Newsletter and the Freeman's Journal). These newspaper records were used to corroborate the start and end of drought, and assess impacts. Figure 2 shows the SPI-12 series for the Island of Ireland composite series.

Figure 1 Distribution of gauges in the Island of Ireland Precipitation (IIP) network. Source: Noone et al. (2016).

Evident from Figure 2 is the relative paucity of severe and extreme droughts since the 1980s. Throughout the record there is evidence for multiple notable drought events. Most severe in terms of their intensity were the drought of 1887 and 1934. By comparison the dry summer of 1995 does not feature as a notable drought event in the island of Ireland series. The most severe drought events pre-date available digital records and emphasise the importance of data rescue and digitisation activities. Figure 3 shows the SPI-12 values across each precipitation station in Figure 1 for the period 1850-2015. During the years 1850-2015 seven major drought periods have been identified with an island wide fingerprint. These are 1854-1860, 1884–1896, 1904–1912, 1921–1923, 1932–1935, 1952–1954 and 1969–1977. These events exhibit substantial diversity in terms of drought development, severity and spatial occurrence.

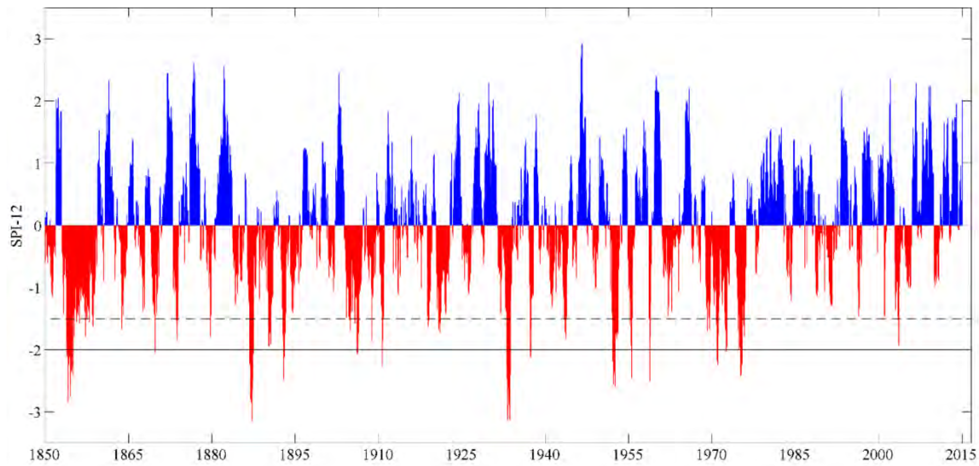


Figure 2 Drought events identified from the island of Ireland composite series using SPI-12. The dashed horizontal line represent the threshold for severe drought and the dashed horizontal line is the threshold for extreme drought. Source: Noone et al. (2017)

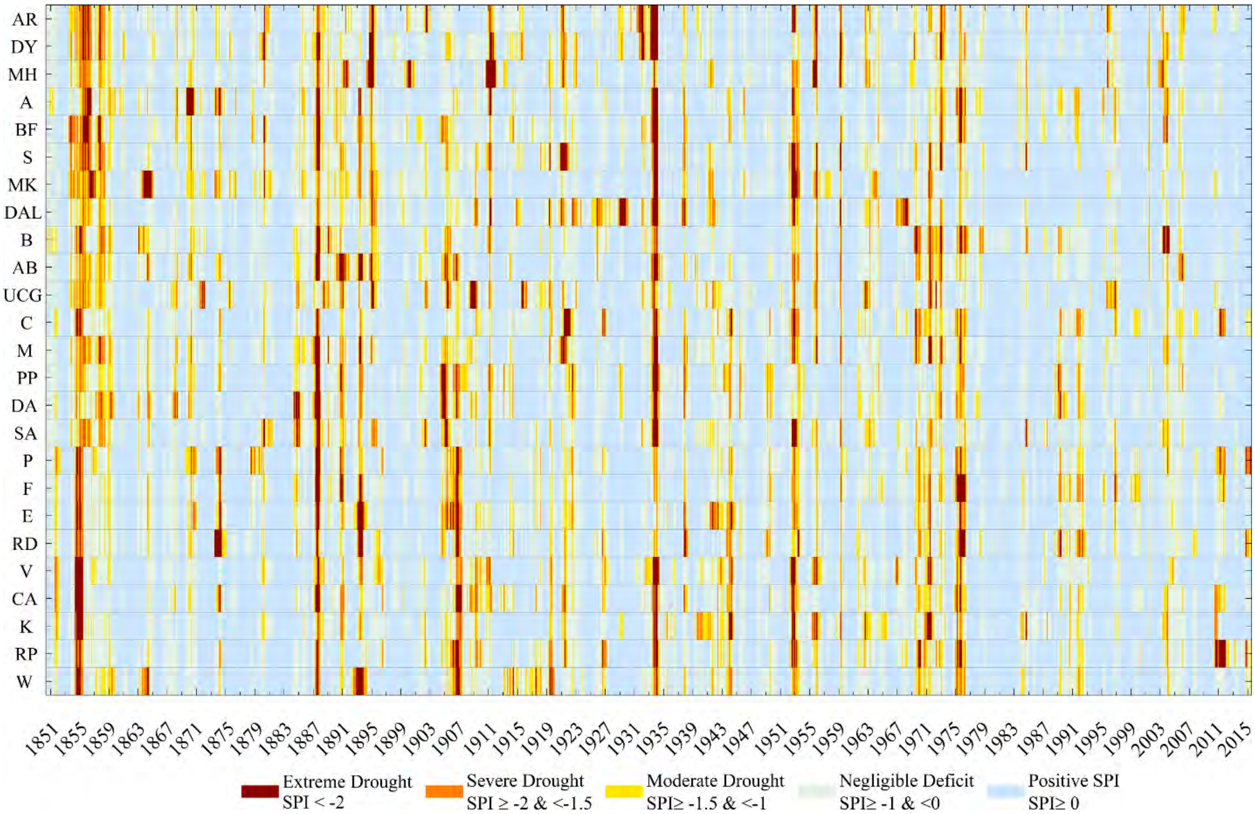


Figure 3 SPI-12 values for all 25 stations in the IIP network. Negative SPI-12 values are colour coded according to severity thresholds to highlight periods of moderate to extreme drought conditions. Source: Noone et al. (2017).

Using newspaper records Noone et al. (2017) were able to track the start and end date of each drought event in print media and gather insights into the key social, economic and environmental impact of each drought identified. Over the period droughts have resulted in agricultural hardship, water resources crises and failures and preceded some of the major famines of the last centuries. While hundreds of newspaper articles were collated by Noone et al. (2017), Murphy et al. (2017) highlight four articles from the newspaper records that define the cultural impact of drought. These range from i) a call from the Bishop of Meath to pray for rain in 1887, a particularly intense drought that most adversely affected the east and south; ii) a proposal for a climate modification experiment to explode dynamite over Dublin city to force rain from the clouds in 1893, a year when Dublin water supplies ran exceptionally low; iii) a satirical poem on water wastage in Dublin, the introduction of water charges and proposals for the inter-basin transfer of water also in 1893; and iv) a poem form 1806 that describes the impacts of drought on the flora, fauna and linen industry of northern Ireland.

INVESTIGATING PRE-1850 DROUGHTS

Additional work has been done to extend our understanding of drought back before 1850 and into the 1700s. Noone et al. (2017) employed gridded rainfall reconstructions for Europe to extend the island of Ireland composite series from 1850 back to 1766/1767. Application of the SPI-12 drought indicator reveals important droughts in the pre-1850 record. These include a particularly protracted drought in at the turn of the 19th Century.

More recently, Murphy et al. (2018) were able to extend the Island of Ireland precipitation series to 1711, creating one of the longest continuous monthly rainfall records anywhere in the world. This long series makes use of the important weather diary collated by Dr. John Rutty in Dublin. Figure 4 presents running decadal annual totals from the 1711 series and provides a comparison with other available long term precipitation record. While the early series is subject to large uncertainties given untypical gauge design, exposure, elevation etc. the particularly dry decade of the 1740s is very apparent. This includes the exceptionally dry and cold years of 1740-1741 which are associated with the 'Forgotten Famine' or Bliain an Áir (the Year of Slaughter) which is estimated to have killed between 13 and 20 percent of the population.

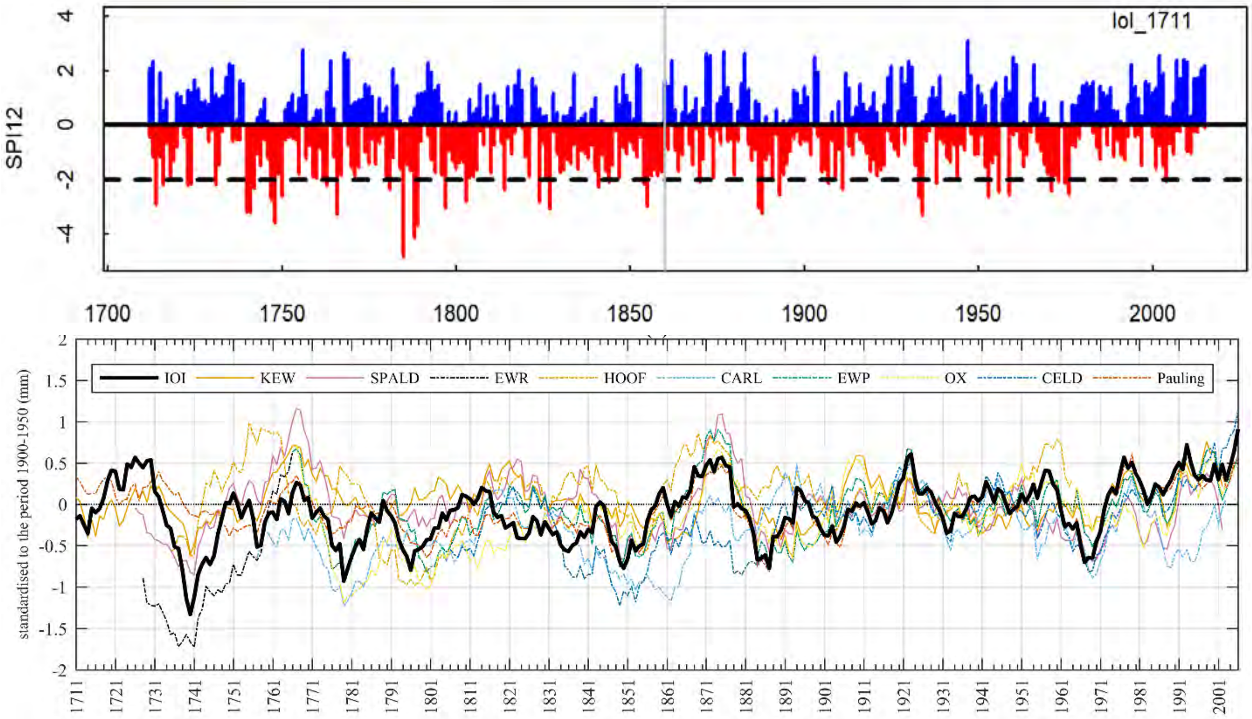
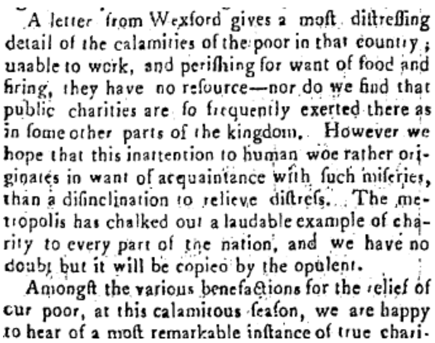


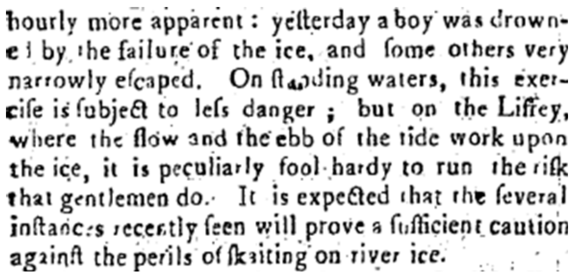
Figure 4 Top: SPI-12 series derived for the island of Ireland for the period 1711-2016. Dashed horizontal line represents the threshold for extreme droughts. Bottom: decadal annual rainfall totals 1711-2016 (black line) in comparison to other long term precipitation records from Northwest Europe (coloured lines) Source: Murphy et al. (2018).

Also presented in Figure 4 is the SPI-12 series extracted for the 1711 precipitation series. One event that stands out is the 1784 drought. It must be noted that the precipitation record is very likely too dry at this time, and thus the event too extreme. However, it is likely nonetheless to be a notable drought in Irish history. The period is marked by weak westerly winds and strongly negative North Atlantic Oscillation (NAO) condition. The period is also coincident with the Laki eruption of 1783-84, with the winters following the eruption being among the most severe on record in western Europe. Given the longevity of Irish newspaper records we can gain an insight into life at this time. Figure 5 shows two extracts from the Freeman's Journal taken from February 1784 that talk about the dangers of skating on the Liffey and the close to famine conditions experienced in Wexford. Also evident from the Island of Ireland 1711 record is that the most recent decades have been the wettest in at least 300 years.



A letter from Wexford gives a moſt diſtreſſing detail of the calamities of the poor in that country; unable to work, and periſhing for want of food and firing, they have no reſource—nor do we find that public charities are ſo frequently exerted there as in ſome other parts of the kingdom. However we hope that this inattention to human woe rather originates in want of acquaintance with ſuch miſeries, than a diſinclination to relieve diſtreſs. The metropolis has chalked out a laudable example of charity to every part of the nation, and we have no doubt but it will be copied by the opulent.

Amongſt the various benefactions for the relief of our poor, at this calamitous ſeaſon, we are happy to hear of a moſt remarkable inſtance of true chari-



hourly more apparent: yeſterday a boy was drowned by the failure of the ice, and ſome others very narrowly eſcaped. On ſtanding waters, this exerciſe is ſubject to leſs danger; but on the Liffey, where the flow and the ebb of the tide work upon the ice, it is peculiarly fool-hardy to run the riſk that gentlemen do. It is expected that the ſeveral inſtances recently ſeen will prove a ſufficient caution againſt the perils of ſkaiting on river ice.

Figure 5 Newspaper articles on weather conditions and hardships of 1784 taken from the Freeman's Journal newspaper Tuesday, February 3rd 1784.

FUTURE DROUGHT

While much recent work has been conducted on historical droughts in Ireland, little work has been completed on the assessment of future drought. As noted above recent years have been unrepresentative of the long term drought climatology of the island. The reason for this is currently under investigation. Assessments of future droughts is a challenging task, especially given the cascade of uncertainty (Smith et al., 2018) associated with assessing the impacts of climate change. For example assessments of changes in key low flow parameters can result in large ranges of change that span even a sign change. A useful and insightful starting point on the assessment of drought conditions under a changing climate has been the work of Matthews et al. (2016) who used an analogue approach to assess the changing likelihood of memorable seasonal extremes under a changing climate.

The summer (June, July, August) of 1995 is both the hottest and driest summer on record. Over the course of the last century the likelihood of a summer as hot as 1995 has increased 50-fold (Matthews et al., 2016). Using a large ensemble of climate model projections for Ireland the likelihood of a summer of extreme as 1995 by the end of the present century can be assessed. Under business as usual emissions of greenhouse gases it is likely that a summer as dry as 1995 will become up to 10 times more likely, while the heat of summer 1995 will likely be considered a cool summer by end of century. It should be borne in mind when thinking about future drought risk that the current generation of climate models (global and regional) show limited ability to capture low frequency variability in summer precipitation. McCarthy et al. (2015) show the important role that the Atlantic Multidecadal Oscillation (AMO) in sea-surface temperatures (SSTs) plays in determining precipitation during this season, yet it is known that climate models capture the atmospheric fingerprint of the AMO poorly (Ruiz-Barradas et al., 2013).

CONCLUSION AND ONGOING WORK

While drought in Ireland may appear somewhat of an oxymoron, our work has shown that droughts are very much a part of the historical climatology of Ireland. The recent past has seen protracted droughts with significant social and economic impact. The catalogue of droughts produced and associated datasets can be used to stress test current water systems to examine resilience and system vulnerability. Moreover, the challenges of modelling the future climate of western Europe means that there are currently large uncertainties over the drought outlook for coming decades. Ongoing work at Maynooth University is seeking to address key gaps in knowledge of past and future droughts. This includes;

- An Irish Research Council (IRC) funded PhD studentship awarded to Paul O’Connor (ICARUS, Maynooth) to link historical climate data and hydrology to reconstruct river flows for catchments in the Irish Hydrometric Reference Network (IRN) (Murphy et al., 2013).
- An IRC Coalesce project entitled ‘Irish Droughts: Environmental and Cultural Memories of a Neglected Hazard’ awarded to Dr. Arlene Crampsie (UCD) and Dr. Conor Murphy (ICARUS, Maynooth). Dr. Crampsie, an historical geographer will lead work on collecting oral histories of drought. Additional collaboration with Dr. Francis Ludlow (TCD) and Prof. Robert McLeman (Wilfrid Laurier University, Canada) will stretch our understanding of drought back over the last millennium and learn from socio-economic responses from another jurisdiction.
- HydroPredict: EPA funded project awarded to Dr. Conor Murphy to examine changes in the flow regime of Irish catchments and future drought under climate change.
- An IRC Employment based scholarship awarded to Ciara Ryan (ICARUS, Maynooth) to work in Met Eireann under the supervision of Dr. Conor Murphy (ICARU, Maynooth) and Mary Curley (Met Eireann) to image and transcribe daily rainfall data from across the island from the late 19th Century.

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HYDROGEOLOGICAL RESPONSE TO THE 2018 DROUGHT IN IRELAND

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ABSTRACT

The winter and spring of 2018 was generally wet. Low rainfall conditions started in May, and absolute drought conditions prevailed from late June until mid-July at weather stations in the East, Midlands, West and South, whilst partial drought conditions prevailed in the North from early June until late July. The drought broke in the West in August, however, in the East and South, rainfall did not exceed the long-term average (LTA) until November.

In general, June to August river flows were well below the long-term monthly averages, and for some rivers the 2018 monthly averages were the lowest experienced in the past three decades. The effects of the drought were also evident in lakes, with surface water-fed lakes reacting relatively quickly to drought conditions while groundwater-fed lakes reacted and recovered more slowly than surface water dominated lakes. Loughs Owel, Lene and Bane reached their low points in October and November 2018. Loughs Owel and Bane recorded their lowest levels since records began, approximately 40 years ago.

Overall, the 2018 drought did not result in exceptionally low groundwater levels, as almost all records (97%) for the long-term stations show the record low being recorded prior to 2018. For recently monitored boreholes, 2018 was a record low groundwater level for 45% of the boreholes that are continuously monitored since 2008.

The effects of the 2018 drought were still apparent in March 2019 in the Midlands and East of the country where surface water, groundwater-fed lakes and groundwater levels remain below long-term averages. Typical seasonal water levels have generally returned elsewhere in the country following rain in March and early April 2019.

Key words: *drought, hydrometric monitoring, groundwater, water resources.*

INTRODUCTION

Met Éireann data (Met Éireann, 2019) for 2018 and 2019 recorded the winter of 2017/2018 as being generally wetter than normal with seasonal rainfall totals above their long-term averages (LTA). This was mainly attributed to December and January as February had below average monthly rainfall. In spring 2018, LTA rainfall values were variable across the country. March had below average rainfall totals at most stations. April had above average totals at most stations. Low rainfall conditions started in May, when nearly all rainfall totals were below their LTA for the month.

In the summer of 2018, drought conditions affected many parts of the country. Apart from Finner, Co Donegal, all rainfall totals were below their LTA for the season. All three months had below average rainfall nearly everywhere with June and July being the driest months. Rainfall was approximately 40%, 70% and 90% of the LTA across the country in June, July and August, respectively. Absolute drought conditions prevailed from late June until mid-July at weather stations in the East, Midlands, West and South, whilst partial drought conditions prevailed in the North from early June until late July. During August, there was a split in the weather with the North and West being cooler and wetter than average, and the South and East being warmer and drier than average. It was not until the 26th of August that widespread heavy rain fell across the whole country.

Autumn 2018 was comparatively dry, with most seasonal rainfall totals across the country being below their LTA. This was attributed to low rainfall in September and October, as November had above average rainfall in most places. For the first time since April 2018, rainfall quantities in November returned to normal levels in the South and East.

The winter of 2018/2019 was drier than average at most weather stations; nearly all rainfall totals were below their LTA for the season. In March 2019, all monthly rainfall totals across the country were above their LTA, making it a comparatively wet month. Rain also fell in significant quantities across the country in early April 2019, which will contribute towards a return to more normal rainfall LTAs.

SURFACE WATER

The EPA published a series of river flow drought maps throughout the summer of 2018. The drought map for the end of September is presented in Map 1. River flows throughout Ireland decreased because of the low rainfall and unusually high temperatures across the country experienced in June. The first signs of lower than normal seasonal flows were experienced in late June, with river flows falling to levels usually not experienced until late August or early September.

In July, the river flows remained low and continued to fall across the country following the sustained period of dry weather. In mid-July, river flow and water level data gathered by the EPA and OPW indicated that approximately 61% (115 gauges) of monitoring gauges were at or below their 95th percentile flow. This 95%ile flow statistic is the percentage of time that flow is exceeded at a monitoring gauge, i.e., the river flow recorded in mid-July had historically been reached fewer than 5% of the time at those 115 gauges. The 95%ile flow statistic is an important low flow metric as the assimilative capacity assessments for wastewater and other discharge licences are derived from this flow statistic, i.e., discharges take account of the 95%ile flow when considering the available dilution. Therefore, the risk of impact on the receiving river ecology is greater when flows fall below the 95%ile. Similarly, if water is abstracted from a river when the flow is below the 95%ile then the assimilative capacity reduces and therefore the risk of impact on the river ecology is greater. A national emergency was in place from mid-June to late August due to concerns relating to water shortages, provision of water supply and the associated environmental impact of discharges during low flows. Overall, river flows increased in the last week of July due to rainfall in the Southern, Western, Midlands and Eastern regions. At this time, the most noticeable increase in flows was recorded in the rivers of Munster and south Leinster, with a lesser increase recorded in the rivers of the East and Midlands.

As a consequence of rainfall in the West and Northwest of the country, the river flows recorded in early August in the West and Northwest were much greater than the flows recorded at the beginning of July. In contrast, due to very low rainfall, the river flows in the Eastern, Southern and Midlands regions were comparable to the flows observed at the beginning of July, i.e., the flows in these regions were dropping back down to at or below 95%ile flows. In early August, approximately 48% (88 gauges) of monitoring gauges were at or below their 95%ile flow, which represented a 22% increase in gauges that were at or below their 95%ile flow since the end of July. The soil moisture deficit was well above seasonal norms and this, along with the low storage in most Irish aquifers explains the flashiness of response in the rivers to rainfall events as overland flow was the dominant mechanism of recharge, rather than baseflow from groundwater.

Overall, river flows increased over the last two weeks of August due to rainfall experienced across the country. River flows were above the 95%ile flow in most monitored rivers by the end of August. The remaining rivers with lower flows were located in a band from Limerick to Dublin and in the

Southeast. In general, June to August flows were well below the long-term monthly averages and for some months, the 2018 monthly averages were the lowest experienced.

In mid-September, river flows decreased in the Midlands and the Southeast regions, however, river flow remained above the 95%ile flow in most monitored rivers in the Southwest, along the Western seaboard and in the border counties. An East / West divide was again apparent in mid-September which reflected the rainfall distribution during this period. In the last two weeks of September, river flows were similar to those experienced in early September (i.e. an East / West divide), with some decreases in river flow in the Midlands and the Southeast and increases in river flows west of the Shannon. River flows remained above the 95%ile flow in most monitored rivers in the Southwest, along the Western seaboard and in the border counties. Map 1 below summarises that approximately 31% (57 gauges) of monitoring gauges were at or below their 95%ile flow.

Overall, the impact of the drought on flows was severe, particularly in July 2018, but wasn't as prolonged or severe as 1975-76 nationally or as severe as 1995 in the midlands and west. The speed at which river flows reduced during a relatively short drought is noteworthy and highlights the relatively flashy nature of Irish river flows.

Table 1 below presents a high level regional river flow summary.

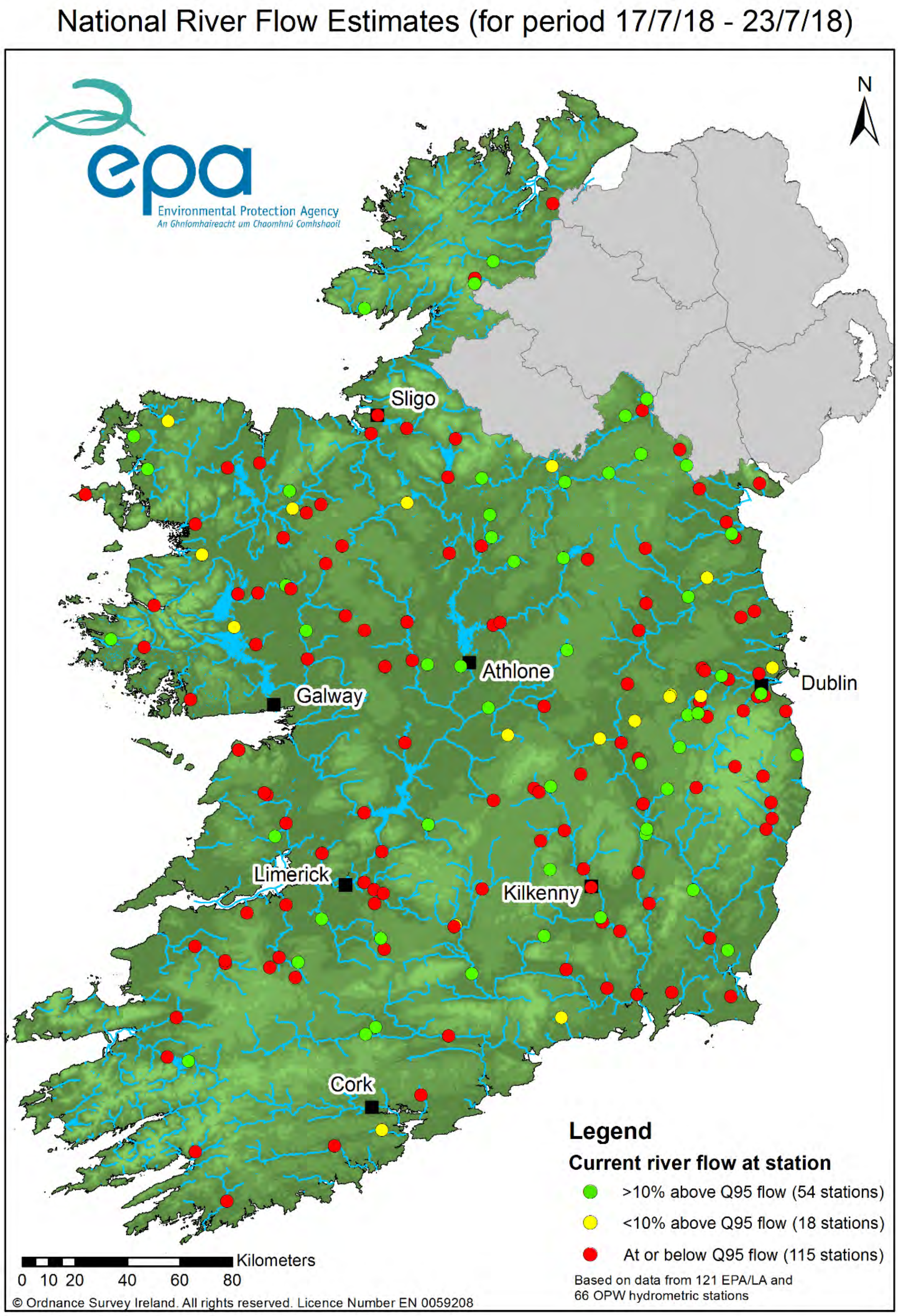
Table 1: *Summary of River Flows, 2018*

Region	Summary of river flows affected by the 2018 drought
Northwest	Only slightly below average and above average from August to the end of 2018.
West	Low in July, but June and August only slightly below average and returned to normal levels in September 2018.
Southwest	Lowest on record in July, very low in June and August; but recovered quickly in late August to normal levels. River Deel remained very low.
Southeast	Well below average since July and remained well below average by the end of 2018.
East	Well below average from June and to the end of 2018, particularly those rivers north of the Wicklow Mountains.

MIDLANDS' LAKES

The EPA monitors water levels at 27 lakes throughout the country. Analysis of the monitoring period of record suggested that the average monthly level in July was below the long-term mean water level at 24 of the 27 lakes. In August, approximately 50% of lakes were below the long-term water level, with a definite East / West divide, with higher than average water levels observed in the Western and Northern lakes. This trend continued into September, with higher than average water levels observed in the Western and Northern lakes, and lower than average levels observed in the Eastern and East-midlands lakes.

For this paper, three lakes are examined in more detail: Lough Lene, in Co. Westmeath, which supplies drinking water to the town of Castlepollard; Lough Owel in Co. Westmeath, which supplies drinking water to the town of Mullingar; and, Lough Bane in Co. Westmeath / Co. Meath, which provides drinking water to the towns of Kells and Oldcastle. These lakes are predominantly groundwater fed and are situated in an area of Dinantian Upper Impure Limestones (GSI, 2019) which is a locally important karstified aquifer (Lk).



Map 1: *National river flow estimates for mid-July 2018*

As can be seen in Figures 1, 2 and 3, the water levels in Loughs Owel, Lene and Bane started falling in April/May 2018, as is the case typically each year. Loughs Owel and Lene reached their low points in October 2018; being 0.41 m and 0.14 m respectively below their mean monthly levels. The levels were slow to increase in November and only rose by a few centimetres. In December 2018, water levels in Loughs Owel and Lene dropped further below the mean monthly levels. Lough Bane reached its lowest level in November 2018, where it was 0.40 m below its mean monthly level. Water levels started to rise in Lough Bane in December to 0.38 m below the mean monthly level. In 2018, Loughs Owel and Bane recorded their lowest levels since records began, approximately 40 years ago. Lough Lene was approximately 0.1 m above its lowest level, which was recorded in 2003.

The three to four-month delay between the end of the drought and recorded lowest water levels in these lakes reflects the buffering effect that the groundwater-dominated hydrology has on these lakes compared to surface-fed lakes. Such buffered inflow increases the resilience of these lakes to impacts from short term droughts, but can be considered a potential weakness during multi-annual droughts, where sufficient winter recharge does not occur.

Following a wet March 2019, water levels in these three lakes increased. The water level in Lough Lene in March 2019 is close to the mean monthly level. However, the water levels in Loughs Owel and Bane in March 2019 remained approximately 0.35 m and 0.20 m respectively below their mean monthly levels. Therefore, more sustained rainfall will be needed to return water levels in Loughs Owel and Bane in to normal levels. Due to the rainfall in March, the risk of an inter-annual drought at the groundwater fed lakes has reduced but remains a possibility if lower rainfall conditions return.

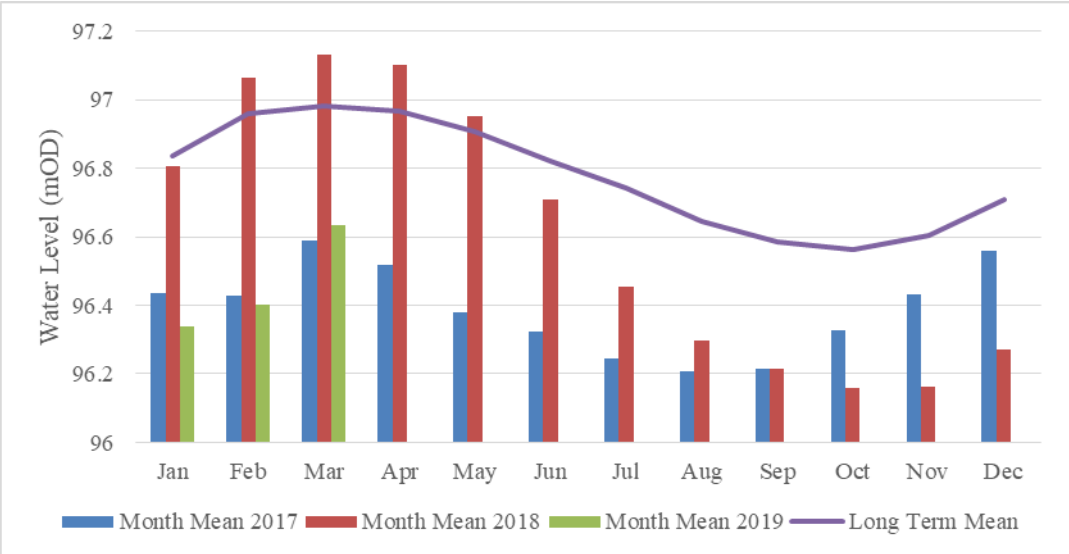


Figure 1: *Mean monthly water levels at Lough Owel, Co. Westmeath (1979-2019)*

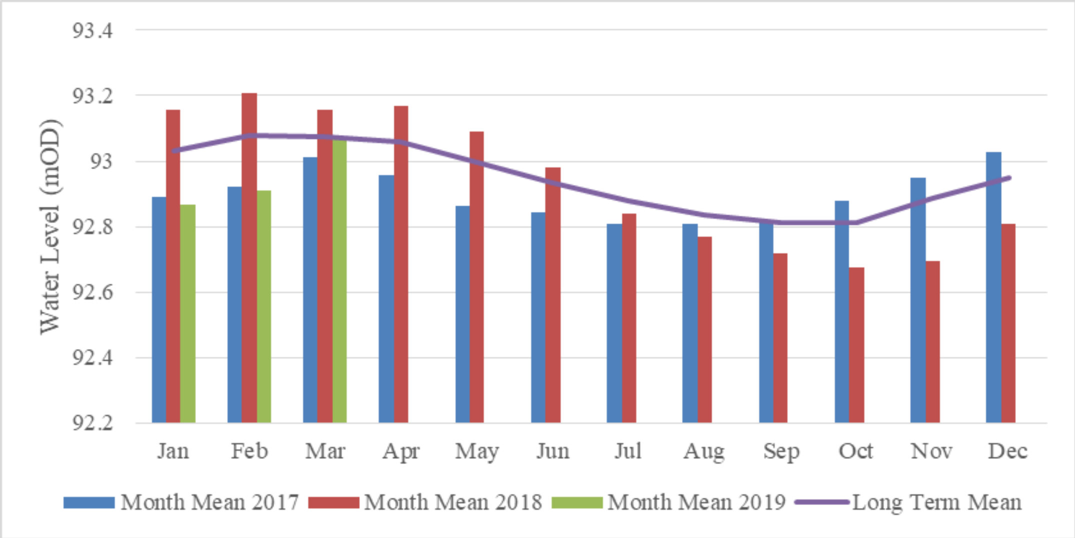


Figure 2: *Mean monthly water levels at Lough Lene, Co. Westmeath (1981-2019)*

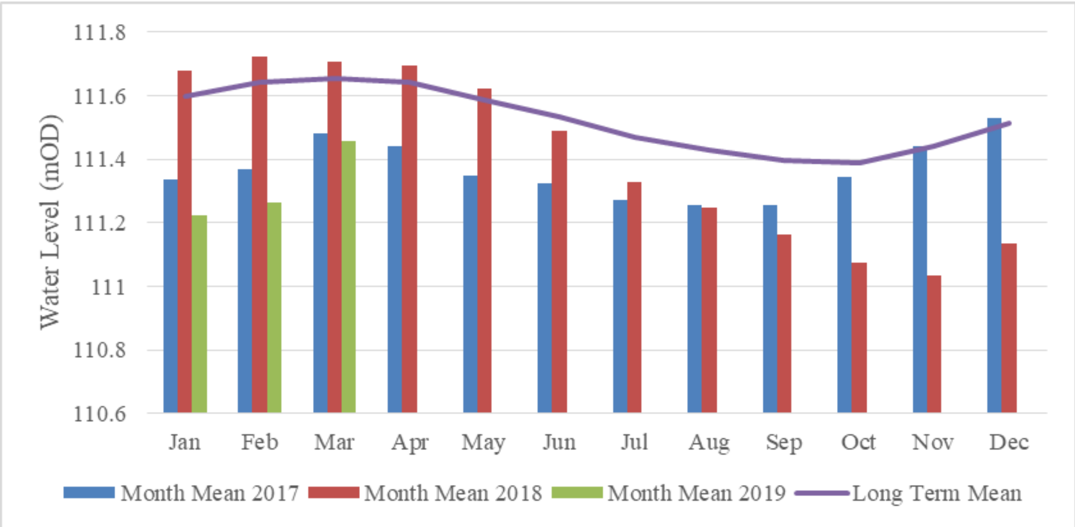


Figure 3: *Mean monthly water levels at Lough Bane, Co. Westmeath / Co. Meath (1978-2019)*

GROUNDWATER
The EPA's National Groundwater Monitoring Network includes monitoring of groundwater levels in approximately 126 boreholes. Roughly half of these boreholes are in six nested clusters in poorly productive aquifers ("PPA sites") across the country, with the remainder focused on monitoring groundwater levels in the more productive aquifers in Ireland.

THE EFFECT OF THE 2018 DROUGHT ON GROUNDWATER LEVELS
Of the 112 boreholes in the National Groundwater Level Network, the monitoring stations can be divided into two groups – the more recent stations (those with data from 2008 onwards) and the older stations (those with data pre-2008). These groups are used for the discussion below.

More Recent Records (boreholes with data from 2008 onwards)
Eighty of the 112 monitoring points in the dataset were monitored for the first time during or after 2008. Of these 80 boreholes, 36 recorded their lowest groundwater level in 2018. The record low year in the remaining 44 boreholes was recorded at another time in the past decade (refer to Map 2 below). Thus, 2018 was a record low groundwater level for 45% of the boreholes that have been monitored since 2008.

Older Records (boreholes with data pre-2008)

Records for 32 boreholes where there was groundwater level monitoring prior to 2008 were also examined. Several of these stations have groundwater level data recorded since the 1970s and 1980s, when they were installed and monitored by the Geological Survey of Ireland (GSI) and/or the Office of Public Works (OPW), including: Borrismore Creek in Kilkenny, since 1975; Rathduff in Kilkenny, since 1981; and, Oldtown in Kilkenny, since 1980.

Only one of these 32 boreholes (Borrismore Creek) had its lowest ever water level recorded in 2018, and the groundwater level recorded in 2018 was only 7 cm lower than the previous record low level, recorded in 1990. Overall, the data captured from the older records in the National Groundwater Monitoring Network implies that the 2018 drought did not result in exceptionally low groundwater levels in Ireland, as almost all records (97%) for the long-term stations show the record low being recorded prior to 2018.

Regional Variations in Low Groundwater Levels

The regional variations in low groundwater levels in 2018 can be seen in Map 3 below. The hydrological year runs from October to September, i.e., it starts when groundwater levels are expected to be at their lowest at the end of the summer / early autumn. Map 2 shows the month in which the minimum groundwater level was recorded during 2018 in the 112 boreholes assessed. There is a clear spatial pattern in the month in which the minimum groundwater level was recorded. Monitoring stations in the West reached their lowest levels a few months before those in the East, with minimum levels recorded in the West in July and August. In contrast, the Midlands and East recorded the lowest groundwater levels in October and November. This is unsurprising, as the drought broke in late July and early August on the western seaboard, whereas more prolonged spells of rainfall did not arrive to the Midlands and East until November.

Groundwater Levels at Specific Example Sites

The groundwater level trends in 2018 are examined using example sites from the East (MB 30, the Curragh, Co. Kildare and OW3D, Bog of the Ring, Co. Dublin), Southeast (Knocktopher, Co. Kilkenny) and West (Lackagh, Co. Galway).

- Borehole MB 30 is located in the gravel aquifer (Rg) beneath the Curragh, Co. Kildare.
- Borehole OW3D is situated in a fractured limestone aquifer adjacent to the Bog of the Ring Water Supply in Fingal, Co. Dublin.
- Knocktopher is installed in Dinantian (early) Sandstones, Shales and Limestones in a Regionally Important Fissured Bedrock Aquifer (Rf).
- Lackagh is located in a Regionally Important Karstified Bedrock Aquifer dominated by conduit flow (Rkc).

As can be seen in Figures 4, 5, 6 and 7 below, there is a higher variation in groundwater level in the Rkc Lackagh aquifer compared to the other sites, which reflects the more dynamic nature and lack of buffering in Rkc aquifers.

Apart from Lackagh, the groundwater levels up to April/May of 2018 were higher than the corresponding groundwater levels in 2017 and the long-term mean monthly levels for these sites. The high groundwater levels coming into the 2018 drought were an important factor in groundwater being able to supply base-flow to rivers during the summer. Had groundwater levels been lower coming into the drought, the surface water levels and flows would also have been lower due to the lower base-flow, resulting in a more severe drought.

In the Curragh (MB 30), the lowest mean monthly water level in 2018 was recorded in November, being approximately 0.5 m lower than the long-term mean value, but higher than the corresponding month in 2017.

In Co. Dublin, at Bog of the Ring (OW3D), the lowest mean monthly water level in 2018 was recorded in October, approximately 0.5 m lower than the long-term mean value. The water level remained 0.5 m below the long-term mean in November 2018. Similarly, at Knocktopher, October was the lowest mean monthly water level in 2018, with a value approximately 0.5 m below the long-term mean. At Lackagh, July recorded the lowest mean monthly water level, where it was 1.5 m below the long-term mean. The month of lowest water level was earlier in the year in the West, due to earlier onset of rainfall.

Given the low groundwater levels coming into January 2019, the risk of an inter-annual drought will remain unless sufficient rainfall and groundwater recharge occur in the spring. The groundwater levels in 2019 for the four sites show some regional variation, as can be seen in Figures 4, 5, 6 and 7 below. In the East, water levels in March 2019 are below their long-term mean values by approximately 1 m and 0.4 m in the Curragh (MB 30) and Bog of the Ring (OW3D) respectively. The water level in Knocktopher in March 2019 is above the long-term mean by approximately 0.3 m. In Lackagh, Co. Galway, the water level in March 2019 is 2.5 m above long-term mean value.

Seasonal groundwater levels in March 2019 in the East appear to be generally lower than normal, levels in the Southeast are normal, and in the West are higher than normal. The rainfall experienced in March 2019 will contribute to increased groundwater levels, however, more sustained rainfall will be needed to return groundwater (and surface water) levels in the East to normal seasonal levels.

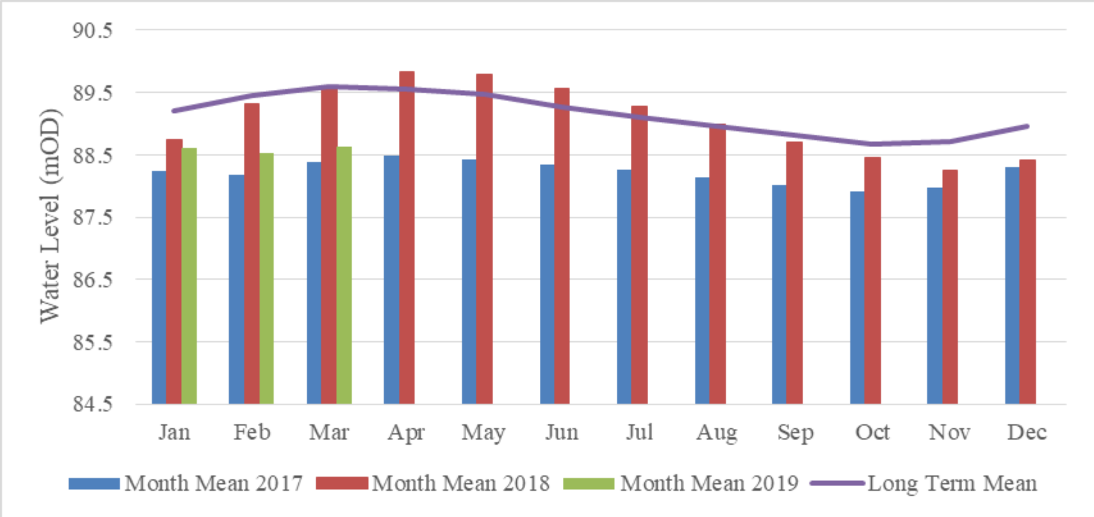


Figure 4: *Mean monthly groundwater levels at The Curragh (MB30), Co. Kildare (2008-2019)*

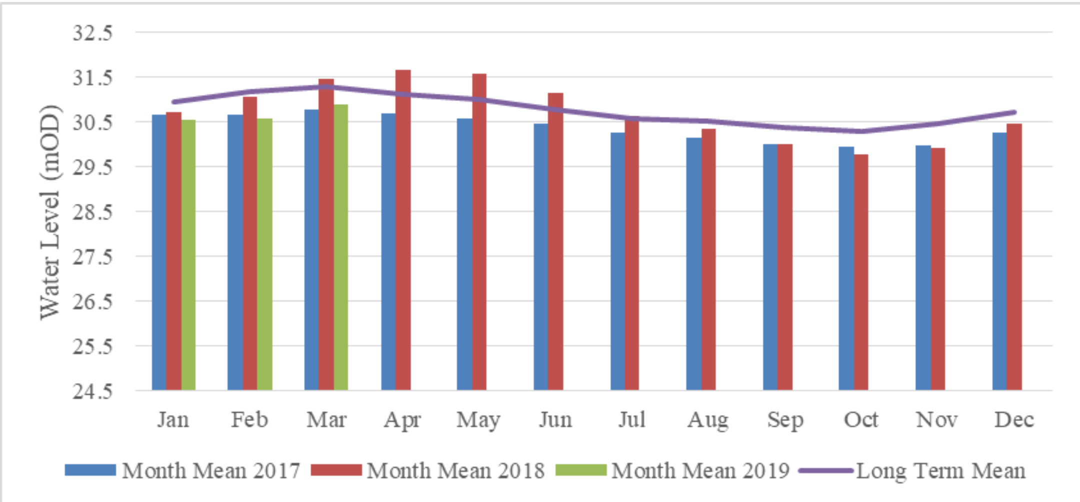
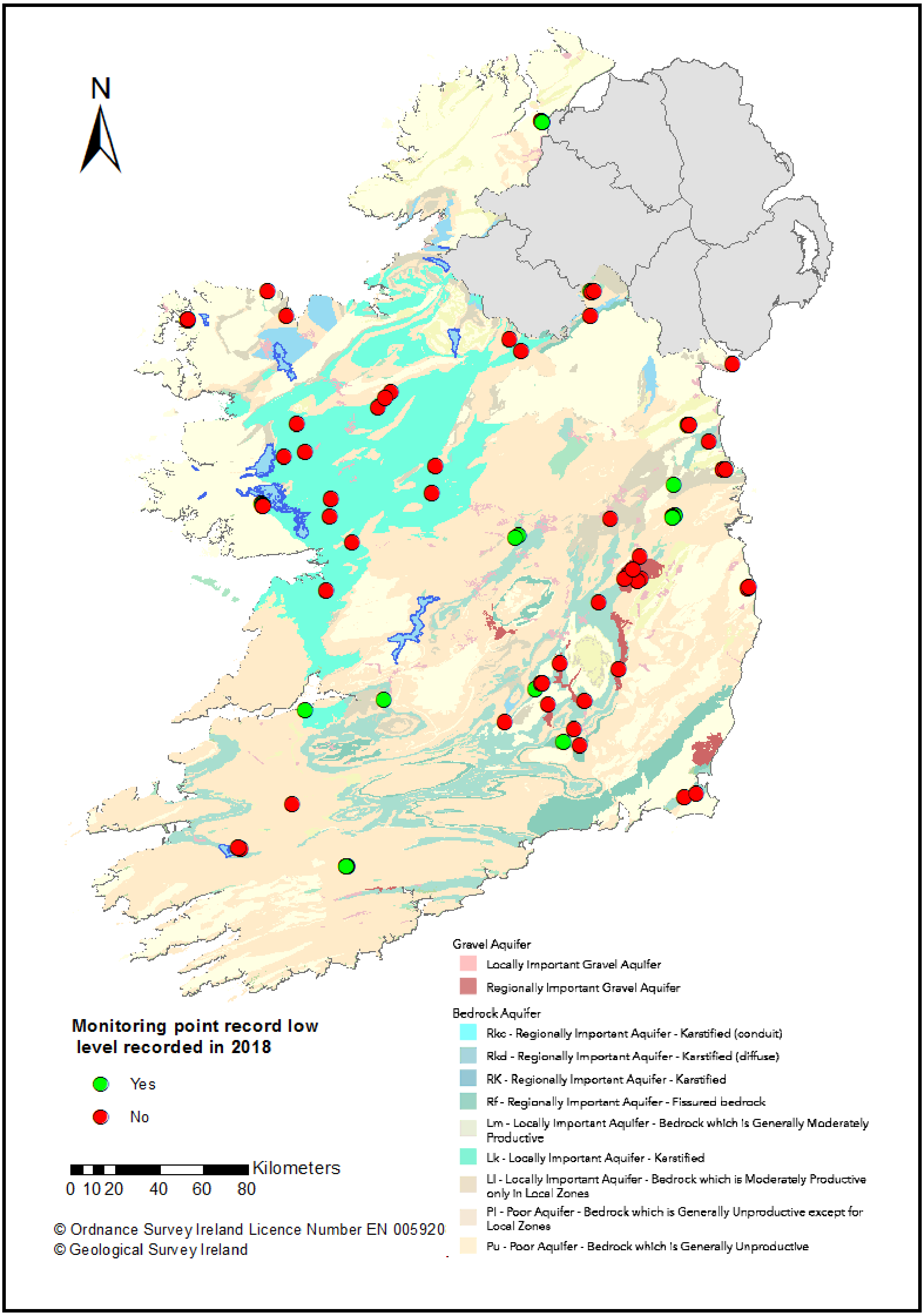
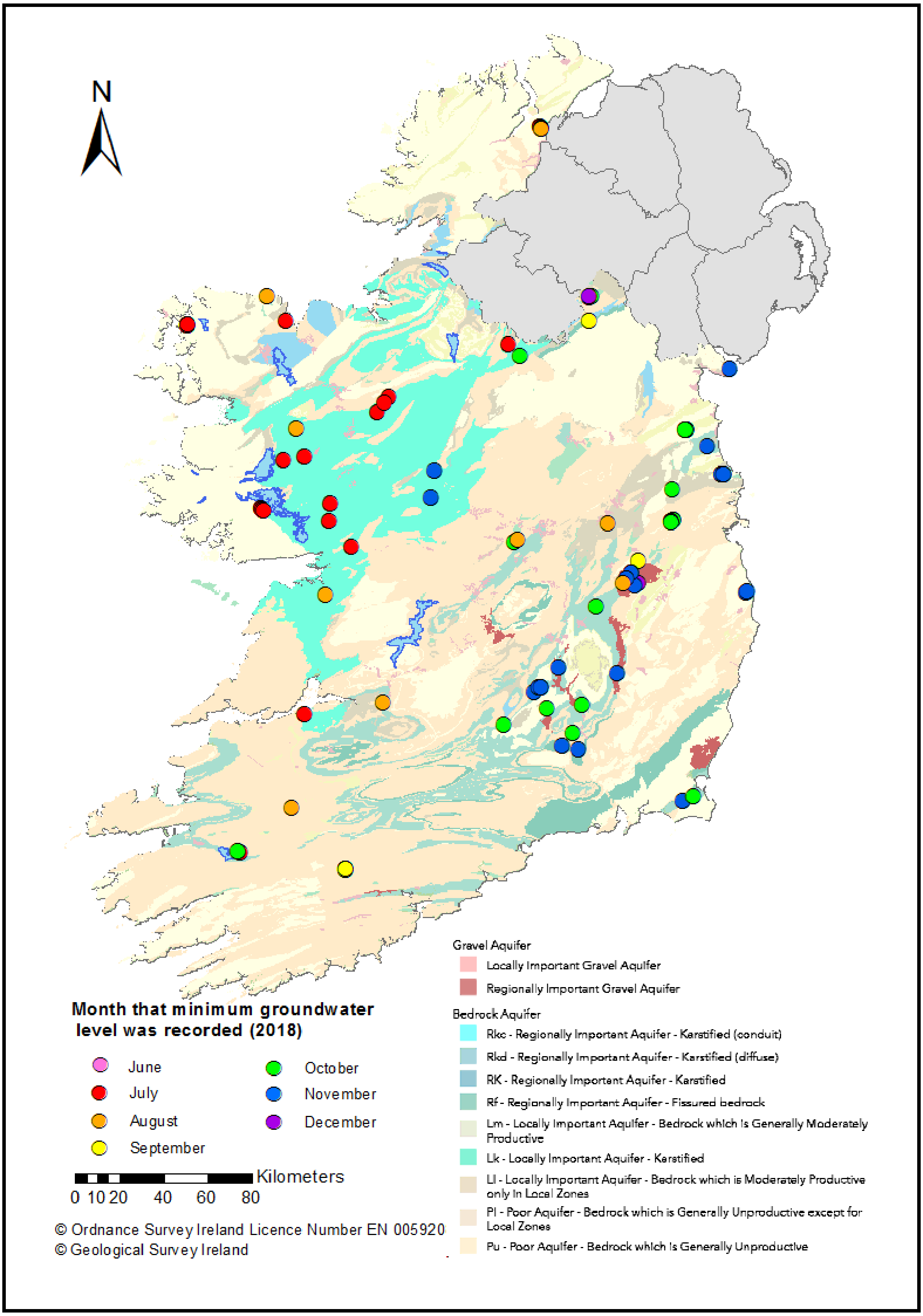


Figure 5: *Mean monthly groundwater levels at Bog of the Ring (OW3D), Co. Dublin (2008-2019)*



Map 2: *Borehole locations where the minimum groundwater levels recorded during 2018 were the lowest recorded for that borehole*



***Map 3:** Month in which the minimum groundwater level was recorded in monitoring boreholes during 2018*

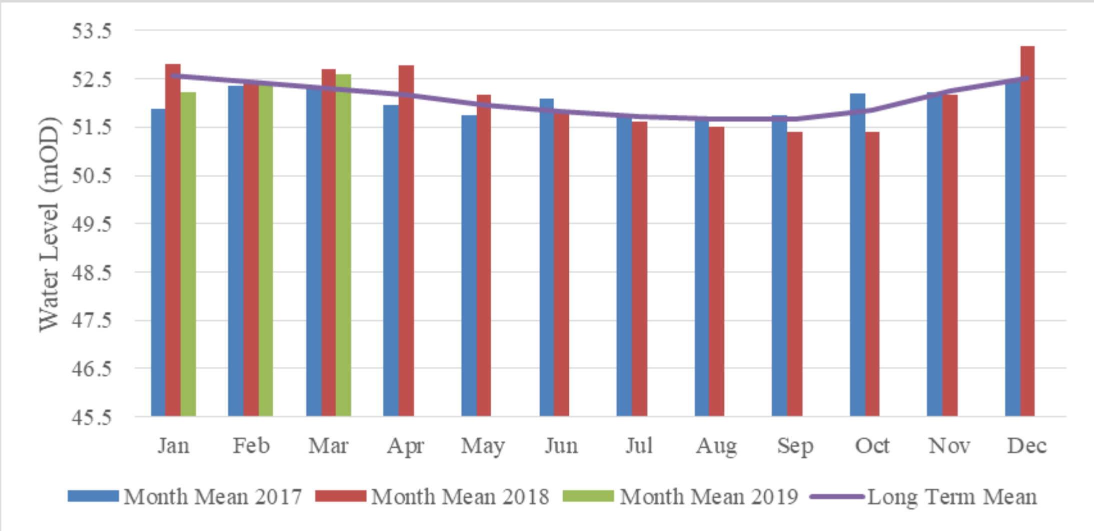


Figure 6: *Mean monthly groundwater levels at Knocktopher, Co. Kilkenny (1980-2019)*

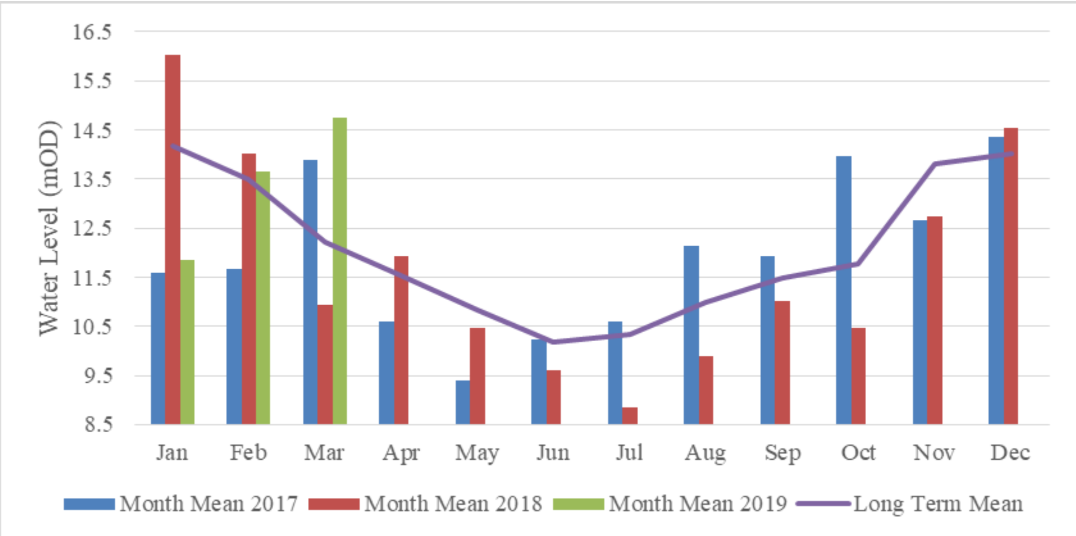


Figure 7: *Mean monthly groundwater levels at Lackagh, Co. Galway (2008-2019)*

CONCLUSIONS

The impact of the 2018 drought on river flows was severe, particularly in July 2018, but wasn't as prolonged or severe as 1975-76 nationally, or as severe as 1995 in the midlands and west. In 2018, Loughs Owel and Bane recorded their lowest levels since records began, approximately 40 years ago. Lough Lene was approximately 0.1 m above its lowest level, which was recorded in 2003. These groundwater-fed lakes are particularly susceptible during multi-annual droughts, where sufficient winter recharge of groundwater does not occur and hence groundwater flow to the lakes is significantly reduced. Water levels in lakes dominated by surface water runoff fell and rose quicker than the more buffered groundwater-fed lakes.

The 2018 drought did not result in exceptionally low groundwater levels in Ireland, as almost all records (97%) for the long-term stations show the record low being recorded prior to 2018. For the more recently monitored boreholes, 2018 was a record low groundwater level for 45% of the boreholes that have been monitored since 2008. Therefore, the 2018 drought should not be viewed as a 'worst case scenario' from a groundwater perspective, and was not representative of either a prolonged severe drought or an inter-annual drought. The high groundwater levels at the start of the summer drought were also an important factor in groundwater being able to supply base-flow to rivers during the summer of 2018. Had groundwater levels been lower coming into the drought, the surface water levels would have been consequently lower due to the lower base-flow, resulting in a more severe drought. Droughts are not uncommon events in Ireland, and recent decades are not representative of longer-term drought patterns (Noone et al., 2017), which indicate that Ireland was historically more drought prone prior to the 1970s.

The effects of the 2018 drought were still apparent in March 2019 in the Midlands and East of the country, where surface water, groundwater-fed lakes and groundwater levels remain below long-term mean levels. However, following increased rainfall in March and April, water levels are returning to typical seasonal norms across the country. Further monitoring over the coming months is required by the EPA and OPW to verify that the recent rain in March and early April 2019 has resulted in water levels returning to more normal levels, and to identify those rivers, lakes and aquifers that may not have recovered sufficiently over the winter and spring.

The future impacts of climate change, such as higher evapotranspiration rates, lower annual precipitation totals, and lower summer precipitation are likely to impact groundwater and surface water in different ways, and it is imperative that such predicted changes are considered during water resources management planning.

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THE SUMMER OF 2018 – A GROUP WATER SCHEMES PERSPECTIVE

Joe Gallagher

National Federation of Group Water Schemes

WHAT IS A GROUP WATER SCHEME?

A group water scheme (GWS) is a community owned water supply responsible for supplying water to two or more house connections sharing a common source or supply. There are 2 types of group water scheme:

1. A GWS with its own source of water - Local group abstracts and treats water from their own source e.g. well, lake and river for distribution to its members (often referred to as a private GWS).
2. A GWS that sources its water supply from Irish Water – Irish Water supplies treated water through the group's pipes (often referred to as a public GWS). The group is responsible for upkeep and maintenance of the distribution network.

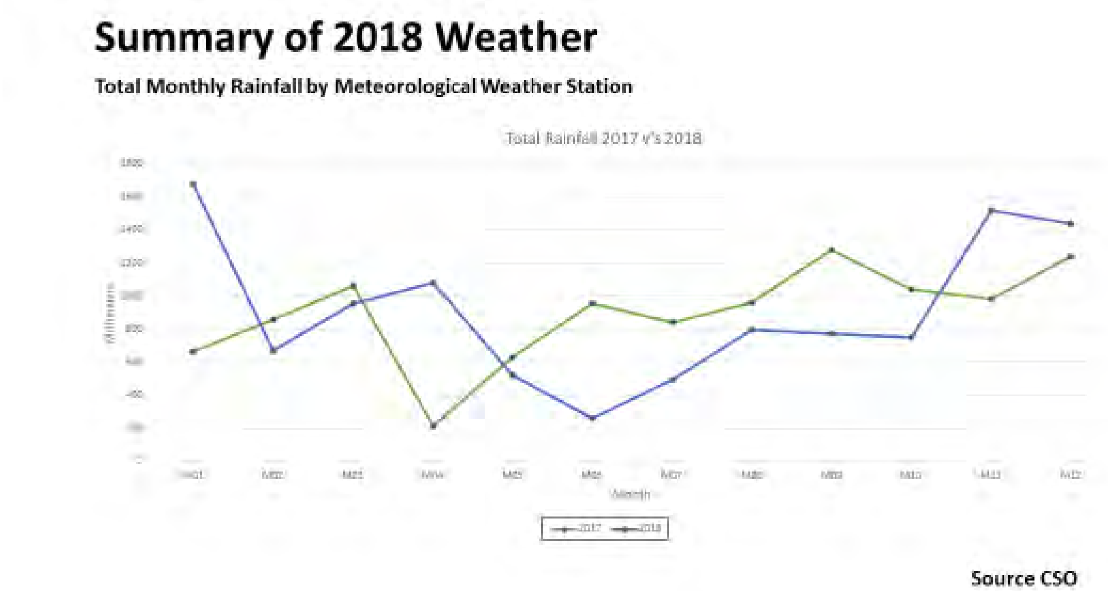
The Group Water Scheme, in both instances is responsible for their distribution network, any maintenance including repair of leaks, scouring of lines and replacement of equipment to a standard to ensure minimum leakage or wastage. The schemes referred to throughout this paper fall into category one above.

THE NATIONAL FEDERATION OF GROUP WATER SCHEMES

The National Federation of Group Water Schemes (NFGWS) was formed in 1997 as the representative and negotiating organisation for community-owned rural water services in Ireland. The objective of the NFGWS has been to secure equality for the sector. The primary 'external' role of the NFGWS is to assist schemes in meeting the challenges of water quality legislation by the installation of water treatment facilities and Source Protection. The NFGWS developed a Quality Assurance Scheme, which provides a guarantee that treated water is delivered safely to members' taps by identifying Critical Control Measures along the GWS system. The role also includes implementation of water conservation measures on GWSs through metering of all connections and creating district metered areas, which also assist to identify critical mains due for replacement. In more recent years it became evident that meeting the numerous challenges of compliance and regulations required professional and dedicated personnel to be appointed and assistance is provided in the recruitment and training of these individuals at both operational and management level. For some GWSs their viability may depend on other options such as rationalisation and amalgamations and focus and support is given to the large numbers of small GWSs that fall into this category.

ANNUAL WEATHER SUMMARY FOR 2018 (MET EIREANN)

The year began unsettled with a mainly westerly airflow for January with Storm Eleanor bringing strong winds on the 2nd. A cold and dry February finished with a polar continental air mass. This brought snow showers with significant accumulations in the East and South. Storm Emma at the beginning of March gave widespread snow in a cold and changeable month. The unsettled theme continued during April with temperatures near normal. May started changeable but overall it was a warm dry and sunny month with high pressure dominating. The settled conditions continued for most of June and July apart from Storm Hector in the middle of June, which brought wet and windy weather briefly. Heatwave and drought conditions in many places towards the end of June continued into early July in several places lasting longest in the South and East. Changeable weather returned towards the end of July and continued in the North and West for much of August. The South and East stayed predominantly warm and dry. September and October were cool and dry, however in September Storm Ali brought the strongest winds of the year on the 19th followed by Storm Bronagh, and Storm Callum on the 12th October. It was mild and unsettled for most of November with Storm Diana on the 28th. Atlantic westerlies dominated in December with Storm Deirdre on the 15th.



DROUGHT CONDITIONS ON GROUP WATER SCHEMES

The first indication that there were issues with water levels on GWS came at the end of June and early July. All schemes were contacted by the NFGWS for an update on their current situation in relation to water supply. At this point there were a small number of GWSs with issues such as, low water levels or where demand had increased, but generally things were under control and manageable.

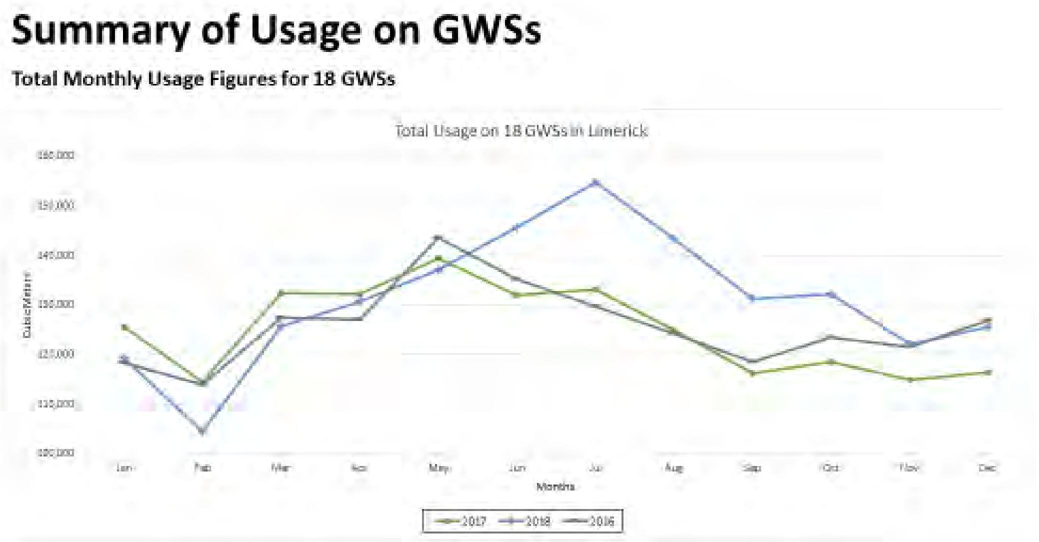
Weekly communications were maintained with schemes during the summer period and the number of GWSs with supply issues started to increase. Virtually all schemes experienced increases in demand during this period with many schemes experiencing water demand levels in excess of what they were able to supply. A total of 32 GWS were affected over the summer and autumn months.

WATER DEMAND ON GROUP WATER SCHEMES

As the weeks progressed the weather continued to be dry with high temperatures, water demand on Group Water Schemes started to rise, placing additional pressure on water sources.

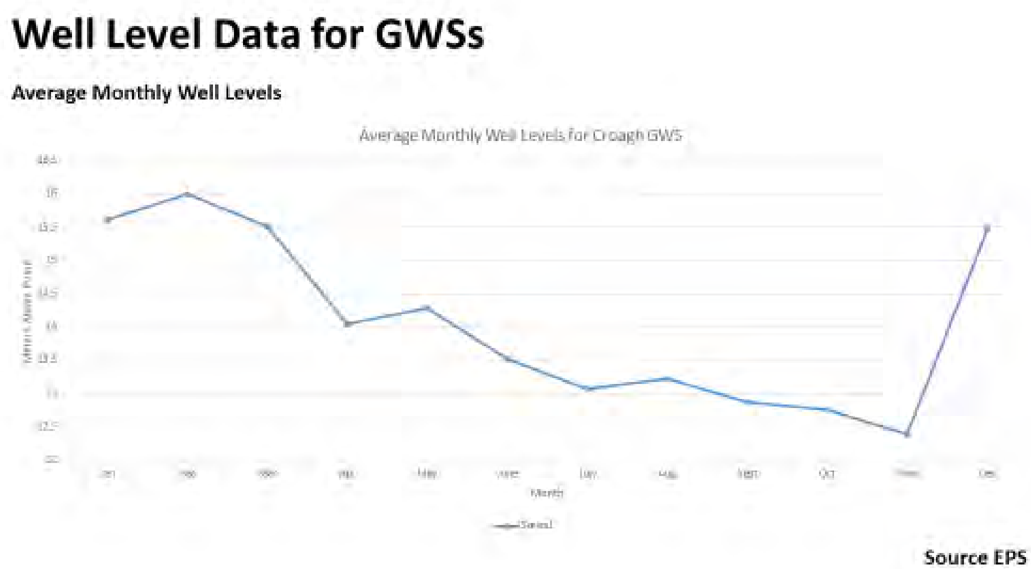
Group Water Schemes noticed an increase in water demand during the drought period and this was down to an increase in agriculture usage (cattle drinking more during the dry period) and the general domestic water usage increase to water gardens, plants, etc.

As the weather was so dry, ground surrounding pipes started to dry out for the first time in years. When the ground started to contract this caused some collars on pipes to pull apart just enough to cause a leak and any leak at this time was crucial – needing to be fixed straight away. In certain areas of the Country, this caused serious issues for some GWSs with a number of leaks identified from collars on water mains.



WELL LEVEL TRENDS

As the drought continued and the usage showed no sign of decreasing, GWSs with groundwater sources continued to monitor the water levels in their wells. Some sources were able to maintain a consistent level but many were starting to notice water levels decreasing to levels never experienced before. Some schemes experienced this trend starting from April onwards, reaching an all-time low during the summer months, but this worrying trend continued for many GWSs until October and even into November. Recharge of many wells was taking longer but unfortunately, time was not something that Schemes were privileged to. Water demand was at an all-time high, due to various reasons, but mainly because people and animals needed water.



COMMUNICATION IS ESSENTIAL

Group Water Schemes have up to date databases for all members, but those GWSs with mobile numbers were able to get information and advice out immediately and this proved vital in making people aware that they needed to conserve water.

METERS ARE KEY

Virtually all Group Water Schemes are fully metered with excess charges in place over and above a free domestic allowance which meant that anyone wasting water was going to pay for it once they exceeded their allowance. This itself was an incentive for most people not to waste water, but GWS did encounter the odd person happy to exceed their free allocation and pay for doing so!

Ballacolla GWS – have all bulk meters fitted with telemetry and all domestic meters fitted with automated meter reading transponders. The GWS experienced high flows during the month of July. By using the technology in place, the Manager and Caretaker would read the bulk meters and monitor what areas were showing increased usage, then they would read all the members' meters in that area and any member with high usage was contacted immediately to make sure that water wasn't wasted or that any leaks were fixed.

WORKING TOGETHER

During the drought period the NFGWS, Irish Water and Department of Housing Planning & Local Government worked closely together with regular updates on water level situations and number of supplies affected communicated on a weekly basis with a Drought Management Report circulated to all parties by Irish Water. The Department of Housing Planning and Local Government committed to assisting any GWS in serious trouble and that needed financial support to relieve the problems. Irish Water also provided assistance where possible and some GWSs availed of the close proximity of water mains by temporarily tapping into the Irish Water network for a short period of time to assist with supply to their members.

This also worked in the opposite direction with a number of GWSs supplying Irish Water with temporary connections to assist with their own supply issues.

There were also some situations GWSs were able to supply neighbouring GWSs with temporary supplies during the period until water levels returned to normal.

OTHER SOLUTIONS

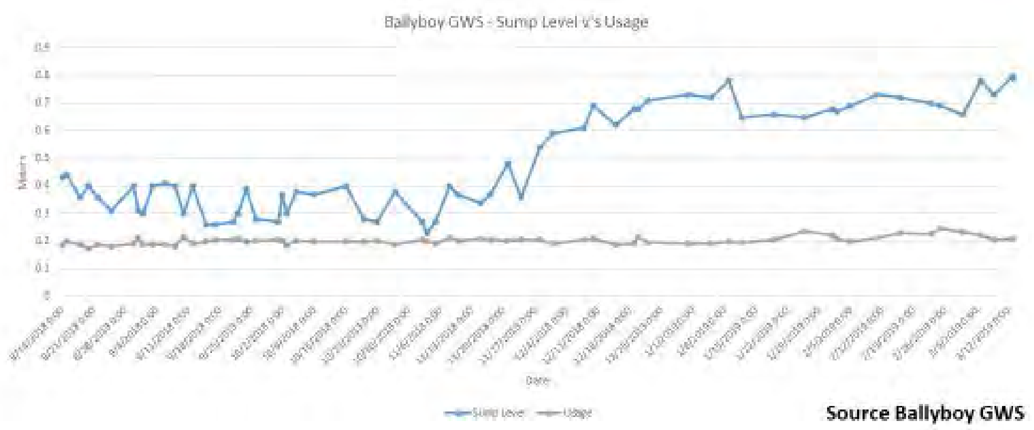
For those GWSs where usage exceeded supply alternative measures were discussed. Some had to reduce flows at night time and this consisted of a full shut off of water from late at night until the early hours of the morning to allow for water levels in the source and/or the reservoir to recover to levels that would allow for pumping or gravity feed to resume the following day. This in turn caused issues as a full shut off of water into the network can cause air to get into the systems and when supply is resumed certain areas can take some time to get back to normal as releasing air from the mains can take time and effort from the GWS Management and Caretakers. If the supply is turned back on too quickly, the increased pressure from this can cause leaks or bursts on the mains. These would have to be fixed immediately otherwise they lead to another way of wasting water.

Others had Pressure Reducing Valves located on their network and these were used to reduce the pressure and flows to various areas of the network allowing the water levels to recover.

Where second sources were available these were brought into production for the drought period. This had to be completed carefully to ensure that water supplied to members was of sufficient quality and fully compliant with the drinking water regulations. In some incidents, additional treatment was required and in other incidents, additional infrastructure was required to link the additional source to the treatment plant.

RELIEF!

Most GWS would have experienced some relief by the end of September or early October while others were still struggling well into late October. Thankfully by November all GWS supplies had returned to normal and the pressure was off Management and Caretakers. Water demand started to reduce on most Schemes and this allowed a number of sources to recover, but water levels were recovering anyway due to more rainfall and recharge to the water table.



LESSONS LEARNED

Meters are essential – whether it's district meters on the water mains or the consumer meters on people's property, they played a vital role. District meters allowed Management to identify areas of the network where leaks may be an issue or wastage may be occurring. Monitoring trends and historical data makes it easier to identify if there is a problem. People's habits and usage can be easily monitored and if exceeding normal levels they can be informed immediately. Charges for excessive usage is also a major water conservation incentive. People were aware that they more they used the more they would pay.

Communication and information as to the current situation on the GWSs was vital in changing people's attitudes towards water usage and water conservation during the drought period. Many GWSs issued advice notices to members and this was helpful in behavioural change. The communication between the DHPLG, IW and the NFGWS was also critical during this period and allowed opportunities for the three organisations to work together on communications and finding solutions to problems.

Both surface water and ground water supplies were affected to various degrees. Treatment plant and storage capacity also contributed to issues and in some instances played more of a role in limiting water production than the source itself!

GWSs that had already reduced Unaccounted for Water to reasonable levels on their networks were less affected as they had the necessary headroom available to meet the increases in demand when it occurred. Schemes that had the necessary infrastructure and management tools in place had better control over water demand monitoring and pressure demand management.

DHPLG are now completing a climate adaptation sectorial review and have established a working group with stakeholders from a range of organisations and agencies to assess and prioritise issues likely to impact on the provision of water services as a result of climate change. The summer of 2018 highlighted a number of these issues which are automatically feeding into this process.

Many GWSs with groundwater sources that previously did not have water level monitoring equipment in place to continuously monitor water levels are now installing such equipment. The issues of 2018 also reinforce the relationship between climate, weather and water with many schemes also installing weather stations at or near water sources.

CONCLUSION

The summer of 2018 will certainly be remembered fondly by many people in terms of good weather, but for a number of GWSs, it was an extremely challenging time. The importance of having the necessary tools in terms of monitoring equipment, infrastructure on distribution networks and procedures in place for emergency planning were reinforced. For GWSs the importance of understanding the water source and its limitations as well as limitations to the treatment infrastructure were invaluable throughout the period. While many schemes were affected during the period, there were also numerous examples of schemes that overcame challenges due in no small part to investment in recent years in water conservation and reductions in UFW levels which provided the necessary headroom during this difficult period. Effective communication both with GWS members and between support agencies and organisation were also key to resolving certain issues. It is extremely important that all lessons learned from this period to help us prepare for similar future events as we all struggle to meet the challenge that climate change poses for every sector.

IRISH WATER'S RESPONSE TO THE 2018 DROUGHT, AS CO-ORDINATED BY THE DROUGHT ACTION TEAM, AND AN OVERVIEW OF THE DEMAND-SIDE AND SUPPLY-SIDE ACTIONS UNDERTAKEN DURING THE JUNE TO SEPTEMBER PERIOD

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1. INTRODUCTION

Irish Water (IW) operates 788 Water Treatment Plants, which produce 1.7 billion litres per day of drinking water, supplying a population of 3.9 million, together with industrial, commercial and institutional customers. In addition, Irish Water operates 1,100 Wastewater Treatment Plants. The Treatment Plants and distribution and collection networks are operated in partnership with 31 Local Authorities, with approximately 3,000 staff directly engaged in the operation of Water Services.

Drought conditions developed across Ireland during 2018. Following a generally cold and wet Spring, rainfall levels fell below average from early May. The dry spell continued for approximately 6 months in the East, Midlands and South, and for 3 months in the North and West. The dry spell was accompanied by high temperatures and long hours of sunshine, particularly through June and July.

The drought conditions had two principal effects on water supplies. Firstly, water resources diminished, reducing the water available for abstraction. Secondly, demand levels increased in many sectors, with greater than normal volumes of water being used by customers. The drought conditions impacted the Supply/Demand Balance on 148 of Water Supply Schemes to the extent that intervention measures had to be undertaken. A further 137 schemes experienced measurable constriction of their Supply/Demand Balances to the extent that they were considered at risk.

During the May to October period, Irish Water closely monitored and managed the water distribution networks in order to maintain service levels for customers, taking intervention measures to retain Supply capacity and reduce Demand insofar as practical and appropriate to the local circumstances. Irish Water's response effort was managed locally and regionally through a network of Incident Management Teams (IMTs) in partnership with 31 Local Authorities, and supported by Contractors and Suppliers. It was co-ordinated centrally by a Crisis Management Team (CMT), in constant consultation with Government and Public Agencies, Stakeholders, Customers and the General Public.

2. INITIAL DROUGHT SITUATION

Weather. Rainfall amounts were high and temperatures low for the first 4 months of 2018.

Figure 1. IW Operational Regions and Met Éireann Reference Weather Station Locations

Table 1. Rainfall and Temperature Statistics for January-April 2018 (Source: Met Éireann)

Weather Station	Dublin	Mullingar	Carlow	Cork	Shannon	Athenry	Knock	Finner
Rainfall (% of mean)	135%	105%	122%	144%	122%	109%	110%	103%
Rainfall Surplus/Deficit v Mean (mm)	78.2	15.9	57.0	167.1	71.8	35.4	42.6	11.8
Av. Air Temp. (C above mean)	- 1.08	- 0.85	- 0.80	- 0.80	- 0.88	- 1.20	- 0.68	- 0.73

From early May, rainfall levels reduced, and air and soil temperatures increased, and the dry, warm weather continued through May and June.

Table 2. Rainfall and Temperature Statistics for May-June 2018 (Source: Met Éireann)

Weather Station	Dublin	Mullingar	Carlow	Cork	Shannon	Athenry	Knock	Finner
Rainfall (% of mean)	20%	43%	25%	57%	52%	57%	66%	66%
Rainfall Surplus/Deficit v Mean (mm)	- 97.7	- 81.3	- 90.4	- 71.1	- 62.8	- 65.3	- 62.2	- 50.3
Av. Air Temp. (C above mean)	0.90	1.80	2.10	1.80	1.80	1.50	2.25	1.85

Water Supply. During June, the effects on water resources became noticeable and measurable at several sites. River and stream flows diminished, lake and impoundment levels dropped at faster rates than in previous years. Observations and measurements by Irish Water and Local Authority Operational Staff were cross-referenced with reports by other agencies, in particular Office of Public Works (OPW), Environmental Protection Agency (EPA), Electricity Supply Board (ESB), Waterways Ireland (WWI). Inland Fisheries Ireland (IFI). By early July, river and stream flows had reached extremely low levels.

Table 3. Hydrometric Stations recording below 95 percentile flow-rate at 11/07/2018 (Source: OPW)

North and West Region	76
East and Midlands Region	43
South and South-West Region	94
Total	213
Total as % of 276 Stations	77%

Water Demand. Water Production patterns for Water Supply Schemes (WSSs) across the country were within the normal range during May, but increased in all areas during June.

Table 4. Treated Water Production tracked across 77 WSSs (Source: IW)

Mean Daily Water Production	May	June	Increase	
	m3/d	m3/d	m3/d	%
North and West Region (5 WSSs)	19,006	19,812	806	4.2%
East and Midlands Region (34 WSSs)	629,035	640,156	11,121	1.8%
South and South-West Region (38 WSSs)	256,640	282,745	26,105	10.2%
Weighted Sum (77 WSSs)	904,680	942,712	38,032	4.2%

Customer Usage. Domestic Customer Meters were read for the month of June and showed an average increase in usage of 32 litres per property per day (c.10%) over June 2017.

Initial Escalation. Towards the end of June, Met Éireann forecast that the hot, dry weather was likely to continue for an extended period. Domestic and Non-Domestic Customer Demand began to rise further from its already elevated levels.

3. INITIAL DROUGHT RESPONSE

Crisis Management Team (CMT). According as the drought impacts on WSSs increased beyond the response capacity of local IW and LA operational resources, IW initiated its Incident and Emergency Response Procedures, and established a CMT on 25th June 2018. The CMT established its objectives, put incident management structures in place, assigned resources, opened up communications channels with Stakeholders and Customers, and set out some immediate response measures.

Crisis Management Objectives. The CMT Objectives fell into 3 categories:

1. Maintain service continuity for Water and Wastewater customers.
2. Identify, analyse and resolve local supply-side and demand-side issues.
3. Ensure efficient and comprehensive communications throughout the Crisis.

Crisis Management Structures. The National CMT interfaced with 4 Regional Incident Management Teams (IMTs). The CMT comprised members of IW's Senior Management Team and representatives from all functional areas. It acted as the National decision-making and coordination forum. It was supported centrally by specialist task groups within different IW Functional areas. Its main focus was on ensuring efficient and comprehensive communications throughout the Crisis, and on providing resources and technical support as required to Regional and Local teams. The Regional IMTs acted in partnership with the 31 Local Authorities, and with local IW teams and contractors, and focussed on maintaining service continuity and resolution of local supply-side and demand-side issues.

Communications. Key Stakeholders were identified and engaged. Extensive communications arrangements were established to ensure efficient internal coordination, and comprehensive, pro-active engagement with media and public.

Table 5. Key Stakeholders

Agency	
NECG	• IW, DHPLG, OPW, ESB, EPA, IFI, HSE.
ESB	• Liffey, Lee
CRU	• Finance / Emergency Expenditure
EPA	• River gauges, Drinking Water Compliance, WW Compliance
OPW	• River gauges
IFI	• River levels, abstractions, temperature of rivers
HSE	• Drinking Water
Met Eireann	• Forecasts / Communications
Emergency Services	• Fire Services / Civil Defence
WWI	• Canal Feeds and Abstractions
NPWS	• SACs
NFGWS	• Public GWS Sources / Private GWS Sources
IFA/ICMSA/Teagasc	• Agricultural Users
IBEC / Chambers	• Business Users
NIW / SW	• Cooperation / Procedures
Public Representatives	• LRSD (Local Representatives Service Desk) Communications

The National Emergency Co-ordination Group (NECG) was established in partnership with the Department of Housing Planning and Local Government (DHPLG) in order to ensure efficient collaboration through the drought period. This comprised representatives of IW, DHPLG and key Water Sector Agencies: Office of Public Works (OPW), Electricity Supply Board (ESB), Environmental Protection Agency (EPA), Inland Fisheries Ireland (IFI) and Health Service Executive (HSE).

Immediate Response Measures. A Water Conservation Order was approved by the IW's Board on 1st July. A Water Conservation Campaign was rolled out, with press releases, media interviews, direct communications with large customers and with vulnerable customers, and the provision of advice and reference information on social media and IW's website. Alternative Water Supplies were sourced and procured for use in areas where restrictions might arise: mobile water tankers, bulk containers and quantities of bottled water. In-flight Projects were adjusted to reduce the volumes of project water use, eg the reservoirs draining and cleaning programme was interrupted until the drought was over. Leak Detection and Repair activity was intensified by the increase in numbers of contractor crews on site, and by reassigning Local Authority staff.

4. ONGOING DROUGHT SITUATION

Weather. The dry weather continued across the country throughout July. During August, rainfall amounts returned to above normal levels in the North and West. The drier than normal weather continued in the East, Midlands and South until the end of October.

Table 6. Rainfall Statistics for May-October 2018 (Source: Met Éireann)

Weather Station	Dublin	Mullingar	Carlow	Cork	Shannon	Athenry	Knock	Finner
Rainfall May-July (% of mean)	37%	44%	41%	55%	64%	65%	73%	75%
Rainfall Aug-Oct (% of mean)	64%	56%	65%	63%	75%	91%	99%	94%
Cumulative Surplus/Deficit v Mean (mm)	- 184	- 234	- 187	- 229	- 133	- 114	- 80	- 80

Table 7. Temperature Statistics for May-October 2018 (Source: Met Éireann)

Weather Station	Dublin	Mullingar	Carlow	Cork	Shannon	Athenry	Knock	Finner
Av. Air Temp. May-July (C above mean)	0.83	1.60	2.13	1.97	1.57	1.17	1.80	1.33
Av. Air Temp. Aug-Oct (C above mean)	- 0.57	- 0.47	0.07	- 0.40	- 0.83	- 1.03	- 0.47	- 0.50

Water Supply. The adverse effects on water resources continued throughout the extended dry weather period. River and stream flows continued at low levels, lake and impoundment levels continued to drop further to lower levels than in previous years. Yields from groundwater sources diminished. According as the rainfall partially recovered in the period August to September, river and stream flows responded relatively quickly, recovering to their base-flow levels. However, the replenishment of lakes, impoundments and groundwater aquifers generally lagged by 1-2 months, and for longer durations in some areas.

Table 8. Hydrometric Stations recording below 95 percentile flow-rate, July to Sept (Source: OPW)

No. of Stations below 95%	11/07/18	16/07/18	30/07/18	07/08/18	09/08/18	21/08/18	04/09/18	14/09/18	21/09/18
North and West Region	76	50	37	26	30	6	6	5	4
East and Midlands Region	43	29	23	25	32	23	28	25	14
South and South-West Region	94	56	34	53	56	56	56	44	7
Total	213	135	94	104	118	85	90	74	25
Total as % of 276 Stations	77%	49%	34%	38%	43%	31%	33%	27%	9%

Water Demand. Water Production patterns for Water Supply Schemes (WSSs) across the country reduced from their exceptionally high June levels. In most cases this arose from the Demand-side interventions, including reduced Customer Usage. In some WSSs the water production reduced because of Supply-side constraints.

Customer Usage. Domestic Customer Meters were read for the month of July and showed very significant reductions in customer usage. Within the Greater Dublin Area (GDA), average household usage reduced by 35 litres per property per day (lpd) from the June levels, and outside of the GDA it reduced by 9 lpd. This indicated a very positive customer reaction to the initial response measures of the Water Conservation Order, Water Conservation Campaign and extensive Communications measures.

Geography and Duration. In line with the geographical spread of the low rainfall, WSSs reached “Drought” or “Emergency” Status all across the country, with the exception of the more North-Easterly Counties: Meath, Louth, Monaghan, Cavan, Leitrim. In the counties affected by drought, the drought duration generally ranged between 3 and 6 months. Aside from the weather influences, the Supply challenges varied scheme by scheme, depending on local factors: capacity, headroom and resilience of local water supply assets and resources. The Demand challenges also varied scheme by scheme, depending on the condition of the network, the availability of alternative local supplies, and the needs and behaviour of the customers, eg agricultural and horticultural users and sports grounds generally had less scope for water conservation than other users.

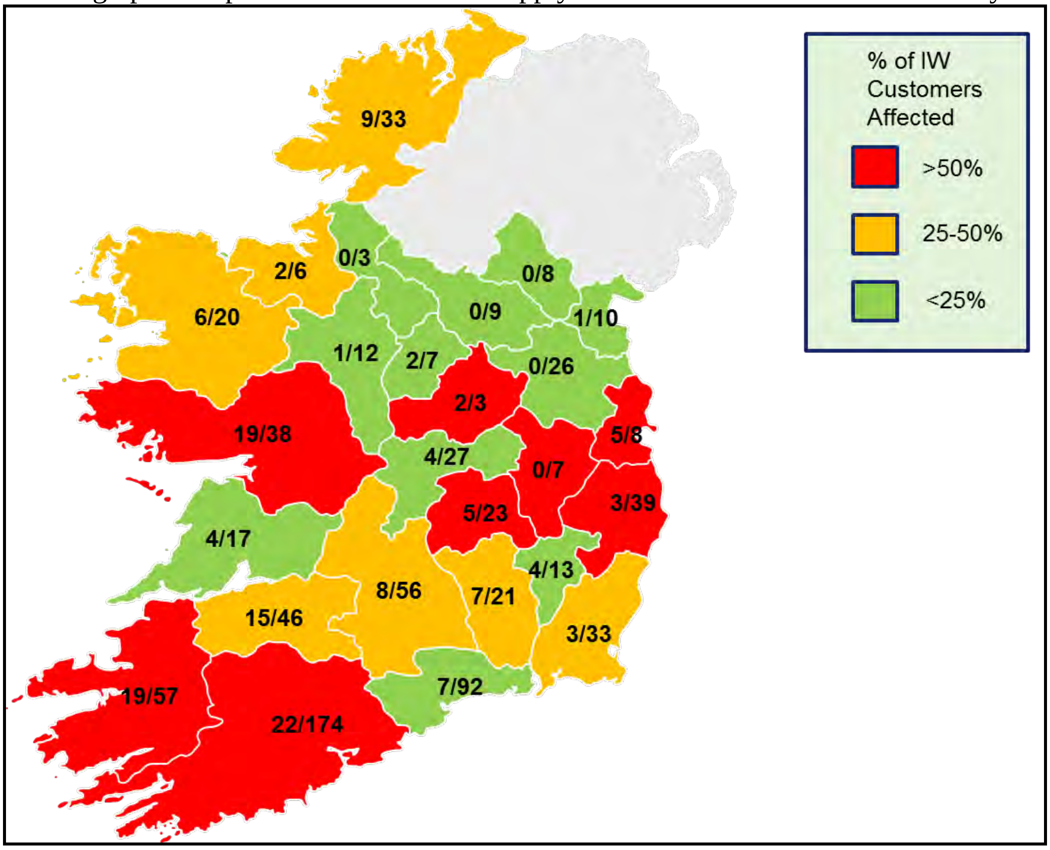
5. ONGOING DROUGHT RESPONSE

National Overview. During the drought period, 148 WSSs reached "Drought" or "Emergency" Status. A further 137 WSSs reached "Potential Drought" Status. "Drought" status was reached when exceptional measures were needed, outside of the normal operational range, in order to maintain continuity of service. "Emergency" status was reached when those measures involved an adverse impact in the level of service to customers – either interruption to supply or pressure reduction that noticeably diminished supply rate. "Potential Drought" Status was reached when local Supply capacity diminished and/or Demand volume increased towards a level of imbalance.

Table 9. No. of WSSs reaching "Drought" or "Emergency" Status during May-Sept 2018

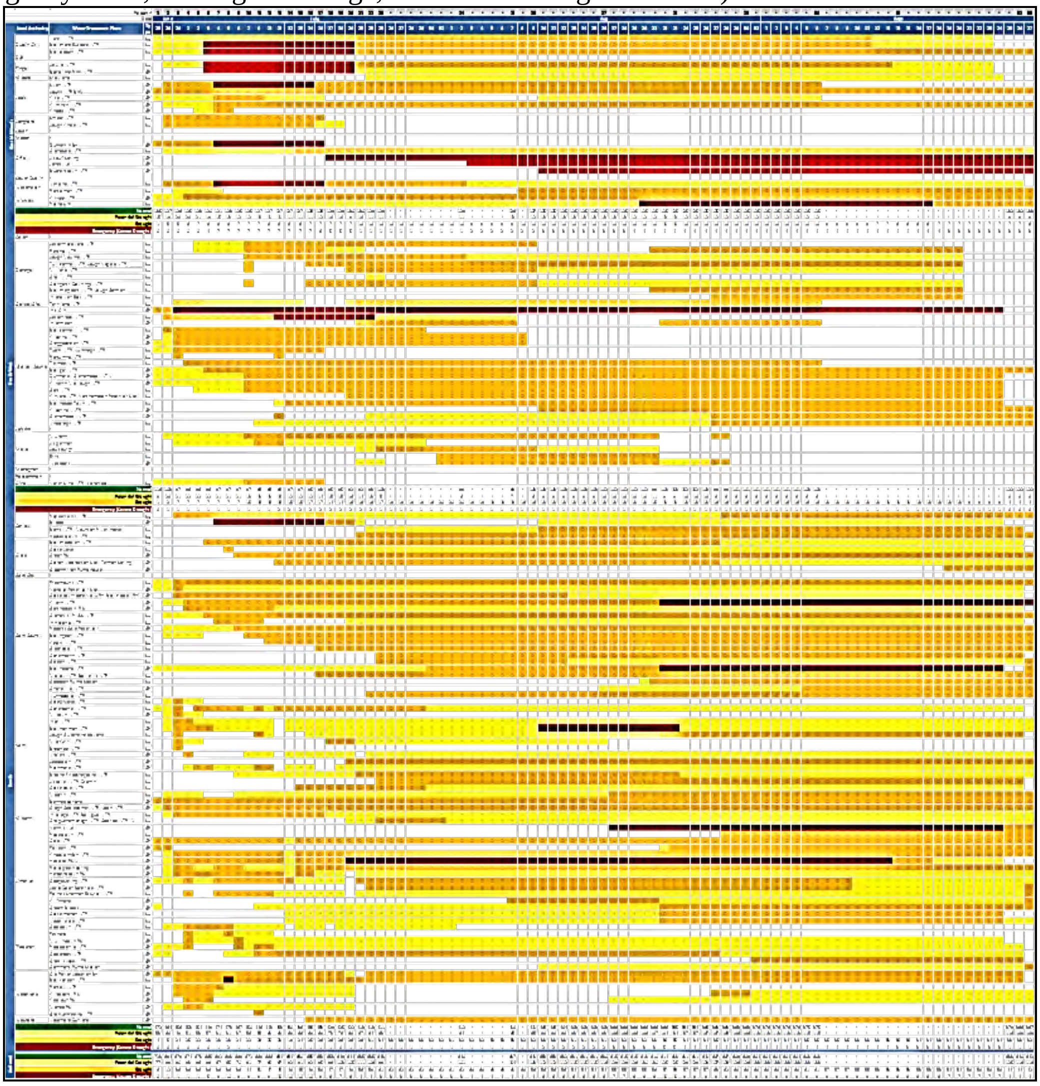
Region	"Drought" / "Emergency" WSSs		
	Surface Source	Groundwater Source	Total
North-West	27	10	37
East-Midlands	9	13	22
South	42	47	89
National	78	70	**148**

Figure 2. Geographical Spread: 148/788 Water Supply Schemes and Customers affected by Drought



Management and Co-ordination. CMT Meetings were held daily throughout July, reducing to twice weekly during August, and fortnightly in September. Drought Status at each WSS was monitored continuously by local IW and LA Operational staff, and an online Reporting Tracker was maintained for reporting on all WSSs. Drought Tracker Reports were generated for each CMT Meeting and in between.

Figure 3. Timeline View of Drought Development across 148 WSSs from Drought Tracker Reports ("Emergency" Red; "Drought" Orange; "Potential Drought" Yellow)



<u>Local Response Measures.</u> The CMT established guidelines for the categorisation of response measures into 5 escalating levels, ranging from Level 1, involving imperceptible impacts on customer service, to Level 5, which involved major usage restrictions including potential water rationing. Regional and Local IMTs applied those guidelines according to local circumstances, capabilities and opportunities, supported by specialist inputs where needed.

<u>Supply-side Interventions for Surface Water Sources.</u> These included:

- Conjunctive use of multiple water sources – eg at GDA, Cork, Galway.
- Collaboration with key parties to optimally manage Liffey, Lee, Corrib, Lough Owel.
- Low-flow interventions at river intakes, including reconfiguration of weirs, pools and fish-passes, and occasionally incorporating cross-pumping and back-pumping arrangements.
- Engagement with IFI, EPA, National parks and Wildlife Service (NPWS) and OPW to safeguard aquatic ecosystems.
- 280 River Abstraction Hydrometrics Surveys.
- 100 Wastewater Hydrometric Surveys.
- Lake Bathymetric & WQ Surveys

<u>Supply-side Interventions for Groundwater Sources.</u> These included:

- Hydrogeology Audits and Step-tests
- CCTV Camera Surveys
- Trial Wells
- Production Wells
- Rehabilitation of existing Boreholes

Malcolm Doak and Michelle Wong expand on these measures in their paper to IAH.

<u>Demand-side Interventions.</u> These included:

- Network Management measures, such as Pressure Reductions, Day-Night Controls, Cross-connections with adjacent Networks, Re-zoning of Networks, Tankering to Reservoirs and Islands, Supply Interruptions and provision of Stand-pipes at key locations.
- Increased Leakage Reduction activity, through mobilisation of more leak location and repair resources, increased activity on private-side leaks, and encouraging the public to report leaks.
- Ongoing Water Conservation Campaign with media and general public, and with specific targeted customers and customer groups: Industry, schools, hospitals, sports clubs, Group water Schemes, Farming sector.
- Further Water Conservation Orders were made by IW Board on 4th July, 1st August, 1st September and 25th September
- Drinking Water Quality protection measures during the drought, including increased network quality monitoring, and interventions where necessary to maintain chlorine residual levels in the network.

<u>Wastewater Interventions.</u> The drought raised challenges for Wastewater drainage networks due to reduced flow-rates, for Wastewater Treatment Plants (WWTPs) due to increased influent concentration, and for effluent receiving waters due to reduced river-flows and increased temperatures, with consequent reduced dilutions and assimilative capacity.

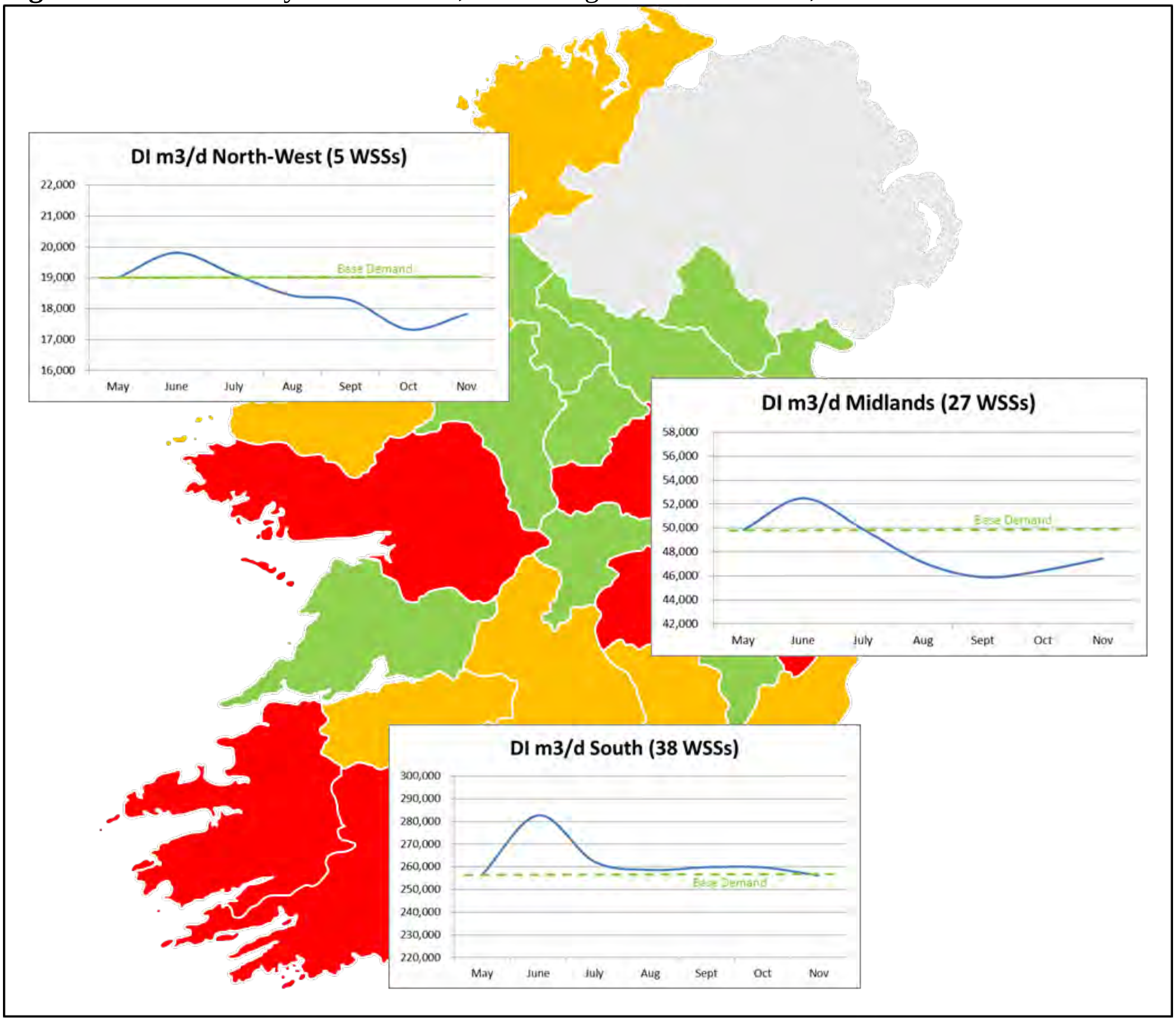
- Wastewater drainage networks: preventative maintenance of overflows and pumping stations to guard against blockages; interventions at pumping stations to minimise septicity and consequent odours.
- WWTPs and receiving waters: Optimisation of treatment processes through increased retention, aeration and desludging as necessary, and at 4 small plants the final effluent was tankered to larger plants as the local receiving water-courses had effectively dried up.

<u>Communications.</u> IW maintained an ongoing Water Conservation Campaign throughout the drought period. In addition, internal communications across all teams and Local Authority partners were maintained. Regular engagement with the NECG ensured coordinated activity and information sharing across the key water agencies. All key Stakeholders had an assigned member of the CMT as their contact point, who kept them up to date.

Customers and the general public were kept informed through the Media, Call-centre and IW Web-site, which were provided with extra staff for the duration, and constantly supported and kept up to date.

<u>Outcomes.</u> IW's Drought management and combination of Supply-side and Demand-side interventions were effective in stabilising the situation. By August, even though the drought was ongoing and increasing in severity in some areas, the Water Production and Distribution Input (DI) across the country had returned to at or below its Base Demand level. The core objectives of Service Continuity, Resolution of problems, and Effective Communications were achieved. A total of 20 WSSs reached "Emergency" Status during the period, of which 9 relatively small WSSs endured at that level for more than 2 weeks. In most cases, even including the "Emergency" Status situations, continuous supply was maintained to all customers. In the few cases where supply interruptions were necessary, these were communicated to customers in advance, and tankers, bottled water and standpipe water at adjacent schemes were provided. In several WSSs, the reduction in DI was sustained beyond the end of the drought as an enduring improvement in the WSS performance.

Figure 4. DI Levels May to November, illustrating Demand Increase, Decrease and Stabilisation.



Closing of CMT. IW closed the CMT on 27th September 2018, when the situation reduced to a level within the capacity of local management. High rainfall levels returned in November to the East and South which helped further to return WSSs to their normal balances.

6. POST-DROUGHT REVIEW

Post Incident Review A Review was undertaken in order to gather lessons learned, and also to improve IW's preparedness for future drought and other Crisis-level events. A substantial amount of Data and Information was collected during the drought management activities, which assisted in resolution of the issues, and is also available for ongoing use in risk assessment, scoping and design of sustainable and enduring resolution measures, and investment planning and prioritisation. Predictive Modelling had been undertaken on the basis of desk-top information and historical records. The drought provided an opportunity to use the predictive models in real conditions and to calibrate and refine the models for improved future use. The drought was severe. At Vartry Water Treatment Plant, the 4-month period May-August was the driest in a 152-year record.

Figure 5. Predictive Model showing Drought Status Bands for Pollaphuca Impounding Reservoir

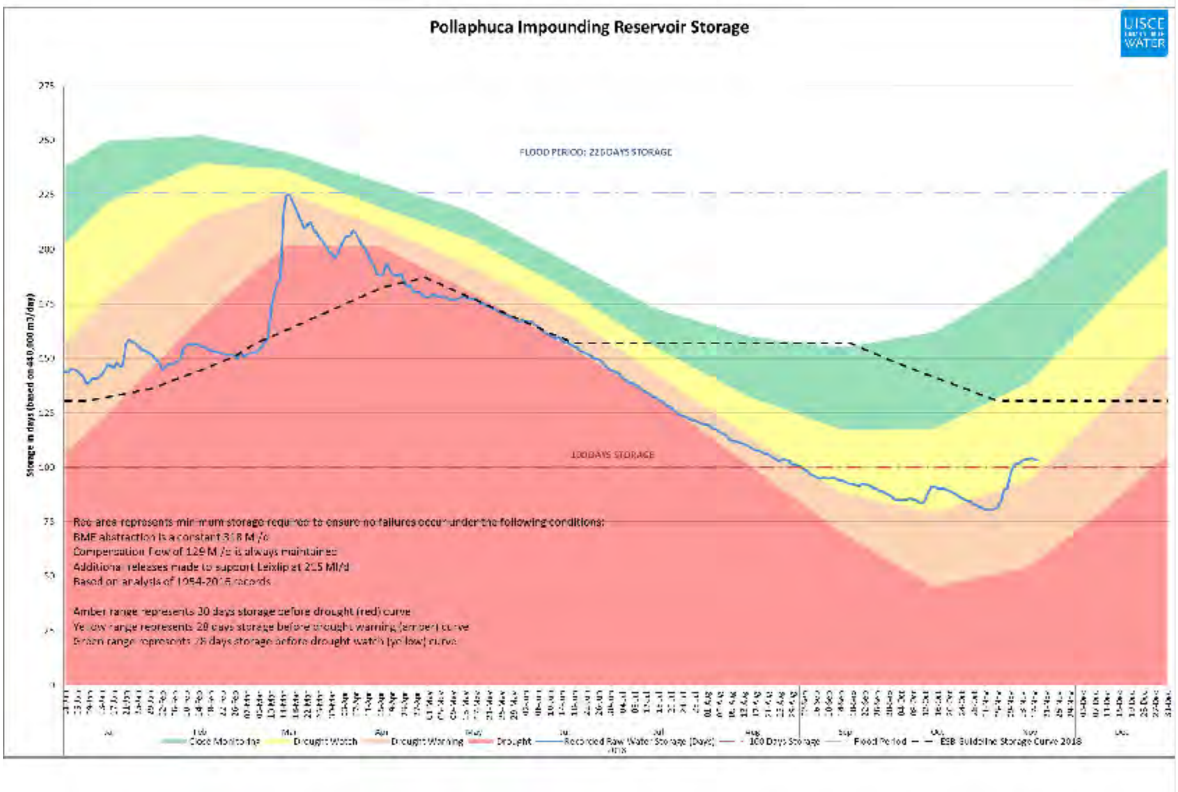
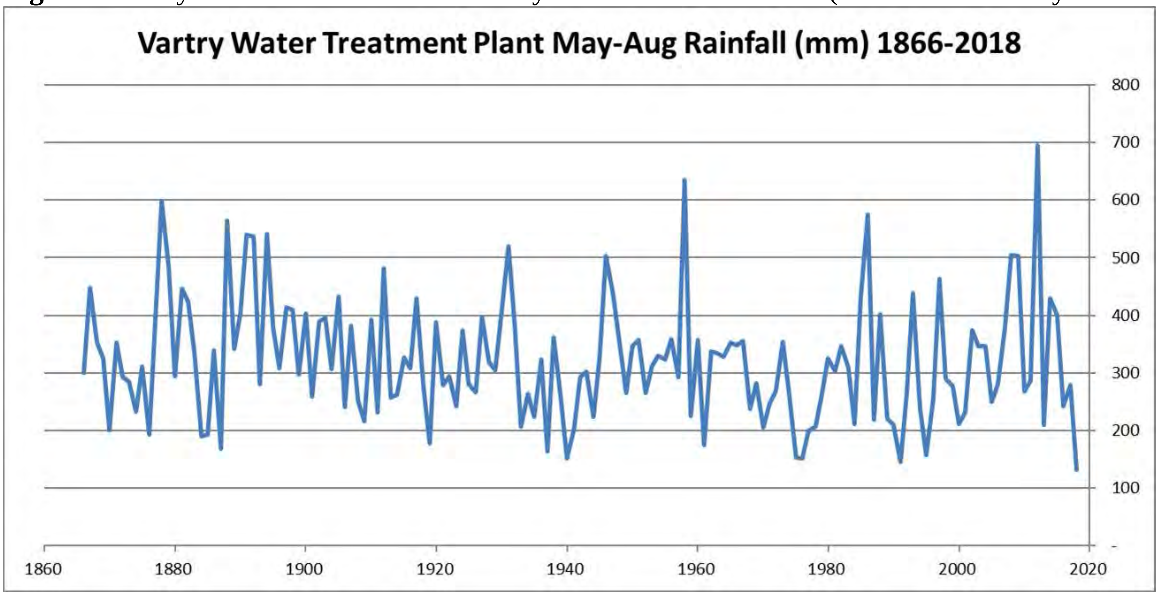


Figure 6. 152-year Rainfall Record for Vartry Water Treatment Plant (Source Dublin City Council)



7. SUMMARY AND CONCLUSIONS

Dry weather conditions developed from May to July 2018 in North and West parts of Ireland, and from May to October in the East, Midlands and South. 148 WSSs reached “Drought” or “Emergency” status in that period. 60% of IW Customers are supplied by those 148 WSSs. According as the drought impacts on WSSs increased beyond the response capacity of local IW and LA operational resources, IW escalated to CMT status on 25th June 2018. IW's Drought management measures were effective in stabilising the situation. IW closed the CMT on 27th September 2018, when the situation reduced to a level within the capacity of local management.

Valuable lessons were learned, and data and information was gathered, which will provide useful inputs into decision-making for asset investment planning, operational management, co-ordination internally and externally, and incident management and preparedness.

ACKNOWLEDGEMENTS

The author wishes to thank all colleagues across IW, Local Authority Partners and Stakeholder Agencies for their contributions to the information compiled during and after the 2018 Drought.

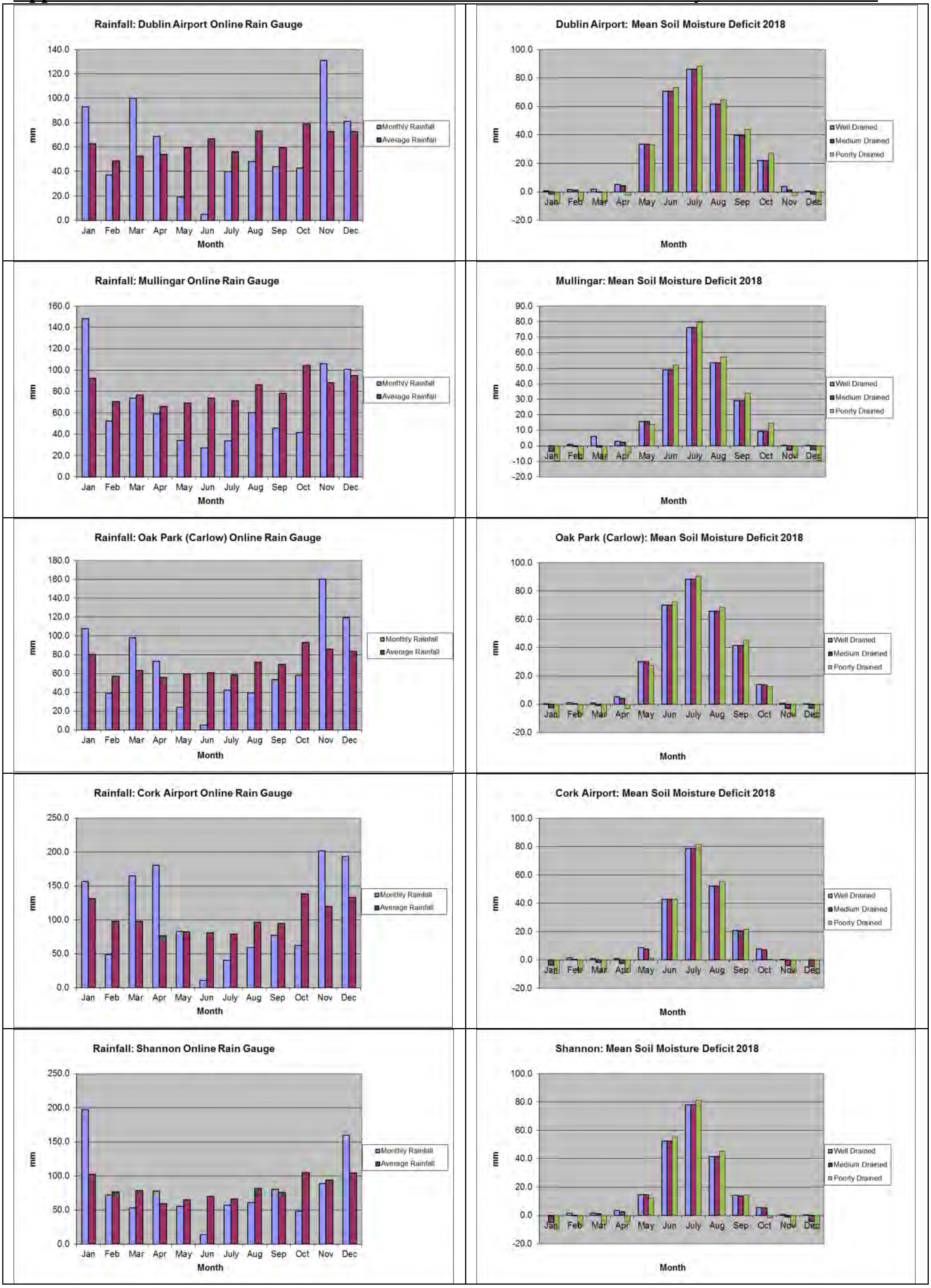
REFERENCES

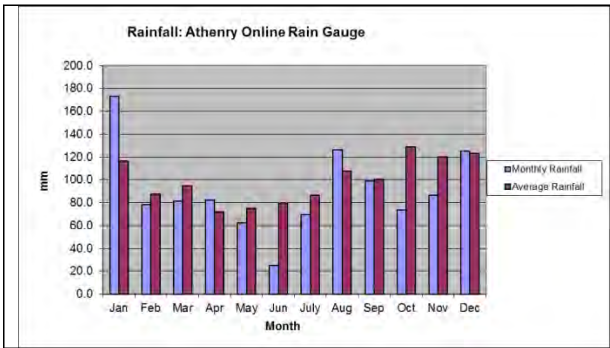
- Irish Water Asset Data-bases
- Irish Water Drought Management Tracker
- Irish Water Incident Management Procedures
- Met Éireann Rainfall and Temperature Statistics
- OPW River and Stream-Flow Gauging Reports
- EPA River and Stream-Flow and Groundwater Gauging Information
- IFI River Status Reports

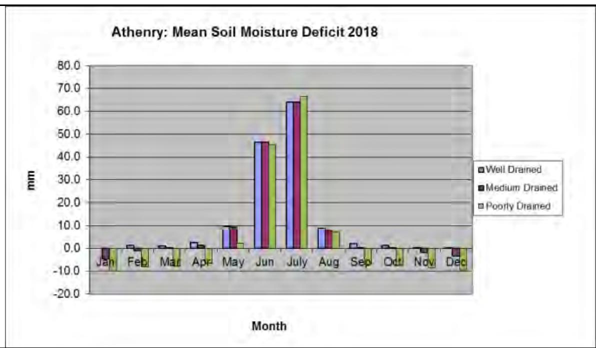
APPENDICES

Appendix 1. Met Éireann Rainfall, Soil Moisture Deficit, Air Temperature Statistics 2018.

Appendix 1. Met Éireann Rainfall and Soil Moisture Deficit Statistics January to December 2018.




Rainfall: Athenry Online Rain Gauge
mm
Month
Jan Feb Mar Apr May Jun July Aug Sep Oct Nov Dec
Monthly Rainfall
Average Rainfall


Athenry: Mean Soil Moisture Deficit 2018
mm
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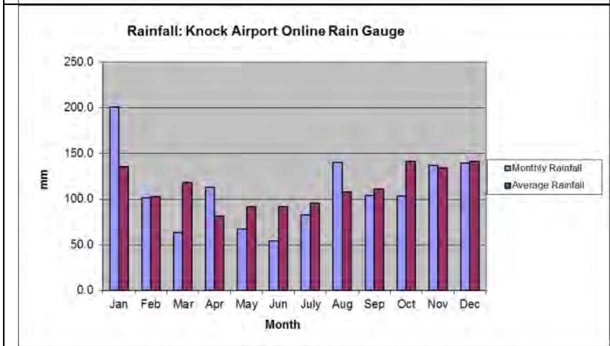
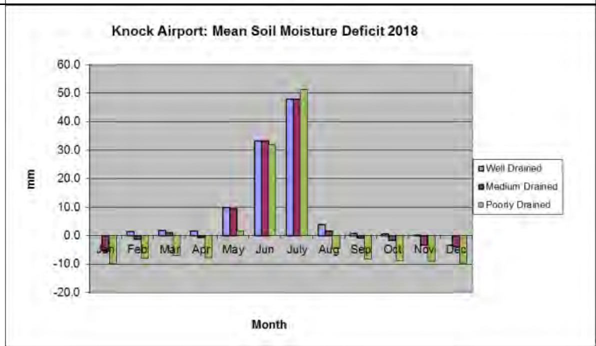
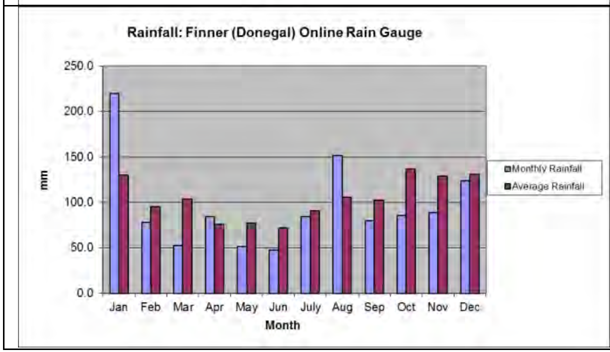
Well Drained
Medium Drained
Poorly Drained


Rainfall: Knock Airport Online Rain Gauge
mm
Month
Jan Feb Mar Apr May Jun July Aug Sep Oct Nov Dec
Monthly Rainfall
Average Rainfall


Knock Airport: Mean Soil Moisture Deficit 2018
mm
Month
Jan Feb Mar Apr May Jun July Aug Sep Oct Nov Dec
Well Drained
Medium Drained
Poorly Drained


Rainfall: Finner (Donegal) Online Rain Gauge
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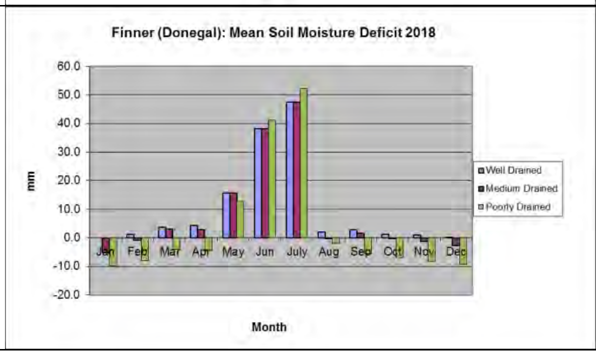
Monthly Rainfall
Average Rainfall


Finner (Donegal): Mean Soil Moisture Deficit 2018
mm
Month
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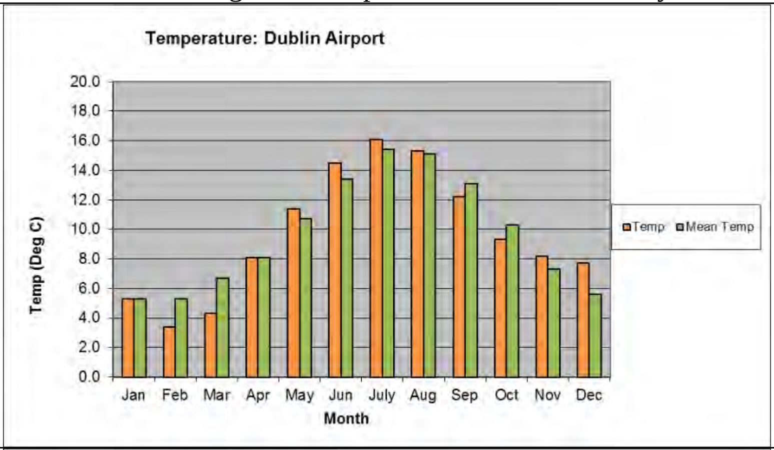
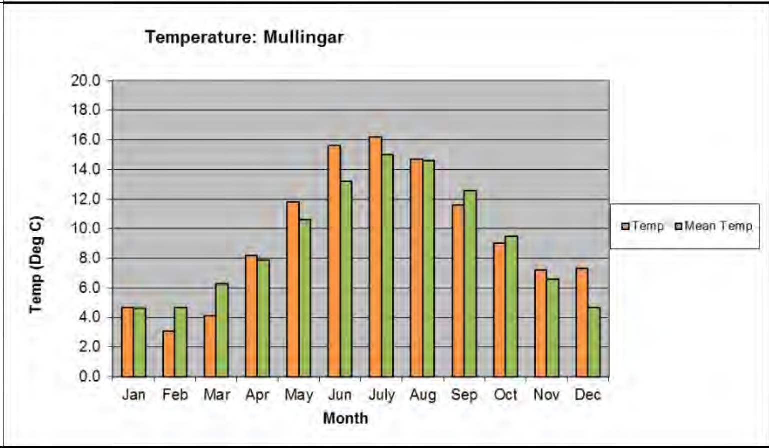
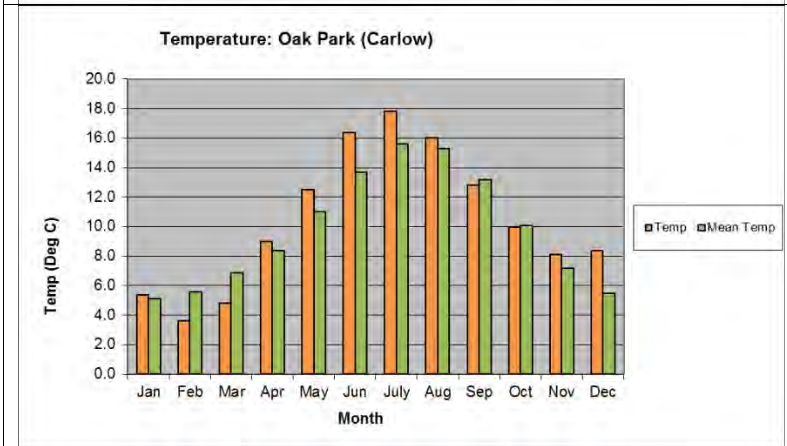
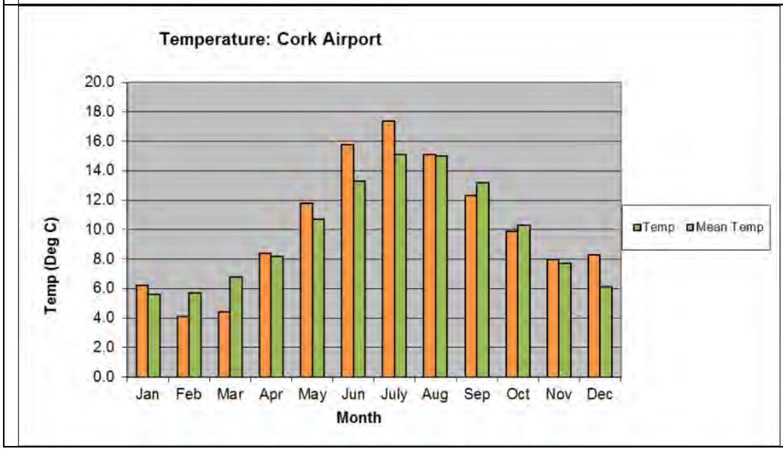
Well Drained
Medium Drained
Poorly Drained

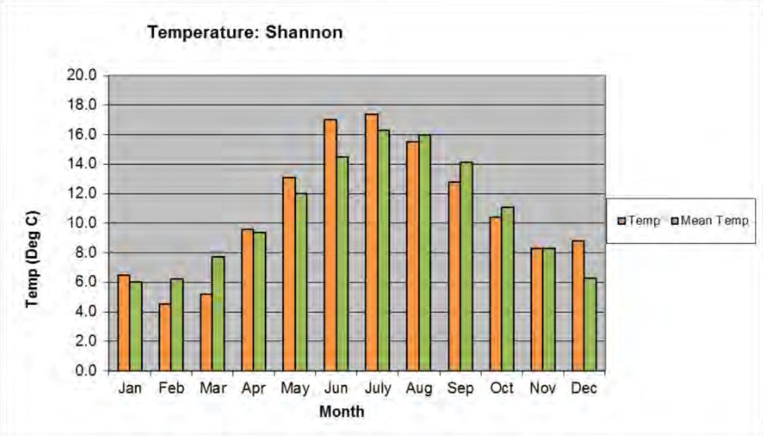
Met Éireann Average Air Temperature Statistics January to December 2018







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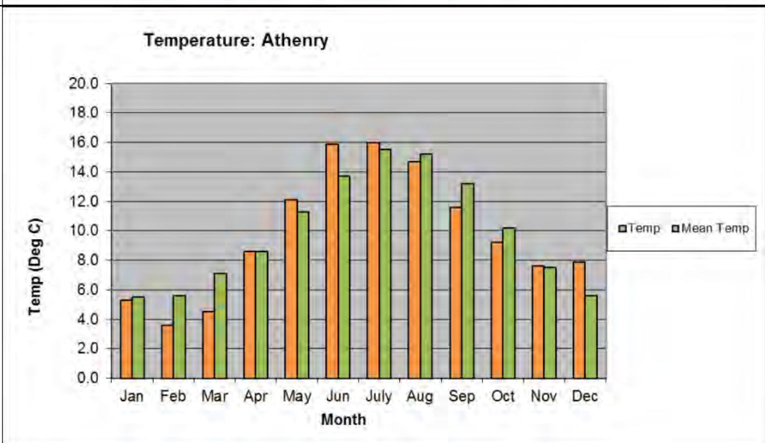
Temperature: Athenry
Temp (Deg C)
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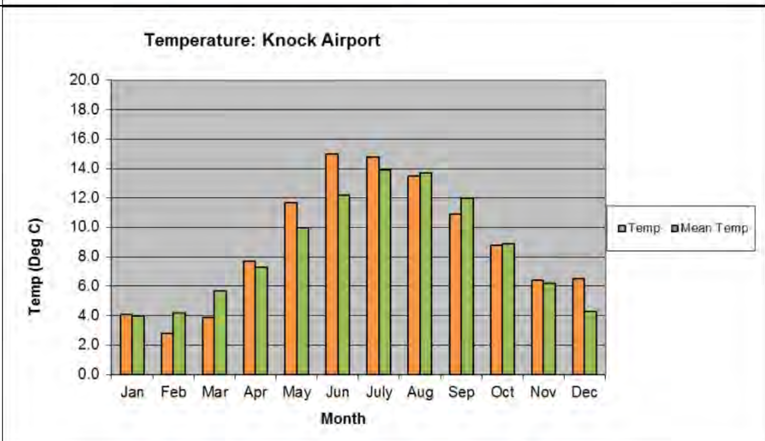
Temperature: Knock Airport
Temp (Deg C)
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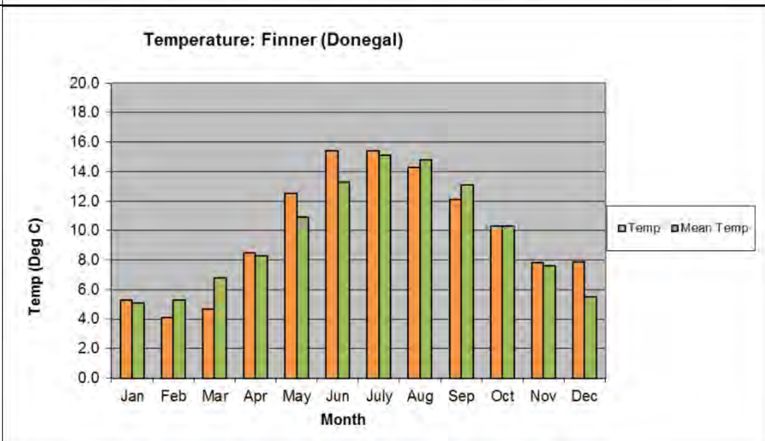
Temperature: Finner (Donegal)
Temp (Deg C)
20.0
18.0
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Jan Feb Mar Apr May Jun July Aug Sep Oct Nov Dec
Month
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Mean Temp

SESSION IV

GROUNDWATER ASSETS SUPPLY-SIDE ACTIONS DURING THE 2018 DROUGHT

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ABSTRACT

This paper offers an overview of the supply-side activities Irish Water employed at our public water supply boreholes during the 2018 drought, and examines the technical approach we undertook at over 70 borehole abstractions which showed deterioration in their operating performance. Key to determining the condition of a borehole in drought and its submersible pump, was the implementation of a Hydrogeology Audit Programme, and the use of down borehole rotating head CCTV cameras, enabling a successful diagnosis and fix, and often a re-start of the borehole water supply. We also provide details of our proposed maintenance strategy for our 850 groundwater assets using the Irish Water Asset Management Lifecycle Delivery method.

1. INTRODUCTION

Ireland's public water supply in the 2018 drought experienced both a serious deficiency of supplies and an exceptional shortage of rainfall over the June to September period. Irish Water, the national utility, issued a *National Water Conservation Order* throughout the 2018 summer months, for all public water supplies. During this period, we undertook several actions to manage the effects of the drought. Actions were broadly split into two groups: demand-side and supply-side. Demand-side actions are those that reduce the demand from our customers for water during a drought, which are discussed by Cuddy (2019). This paper offers an overview of the supply-side activities Irish Water took at our public water supply boreholes (springs excluded) in the 2018 drought, and examines the technical approach we took at over 70 borehole abstractions which showed reduced operating performance.

2. GROUNDWATER SOURCES

Irish Water submitted its inventory of groundwater (GW) and surface water (SW) sources to the Register of Abstractions, managed by the Environmental Protection Agency, during November 2018 (see Figure 2). Irish Water have approximately 850 GW abstractions (350 SW), as 670 boreholes and 186 springs[1] supplying 280 MLD[2] of raw water into supply at 735[3] water treatment plants. There are 118 wellfields, some of which host the biggest abstractions, supplying 100% groundwater into town supplies, such as at Portlaoise (7.5 MLD [4]), Dungarven (5.5 MLD), Gorey (5 MLD), Charleville (3.5 MLD), and Bennetsbridge (3 MLD).

[1] Note: 770 are of 25 m^3/d, or more. Only 770 were entered onto the national register since they exceed the 25 m^3/d threshold

[2] National usage is 1650 MLD (of which 280 MLD is groundwater), with Dublin requiring 610 MLD.

[3] WTP national count is 790. Although GW is 17% of supply, it supplies 95% of the WTPs (735).

[4] 1 MLD = 1000 m^3/d = 1,000,000 L/d = 12 L/s. Hydrogeologists often rate borehole flow at L/s. 1L/s = 86 m^3/d or 0.09 MLD

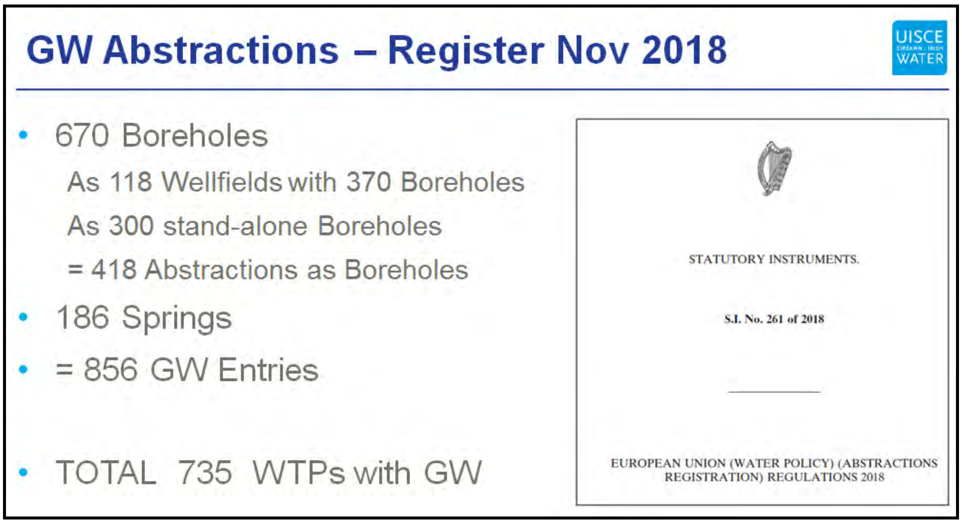

Figure 2. Synopsis of the Groundwater entries submitted to the EPA Register of Abstractions in November 2018, the first time a national picture of the number of national public supply GW Assets has become available. IW made the decision to submit all supplies (770) to the national register, since it records only abstractions greater than the 25 m^3/d threshold.

3. GROUNDWATER DROUGHT IN THE UPPER PALAEOZOIC

Irish Water carried out a review of UK water utilities to determine best practice for the management and maintenance of GW assets situated in similar geology to that of the Irish Water GW Assets, since the Upper Palaeozoic aquifers share fracture flow and conduit karst flow (in limestones). Severn Trent has 133 groundwater and 22 surface water treatment plants, and its territory specifically shares the same Carboniferous Limestones geology to that of Ireland (see Figure 3).

As in Ireland, Severn Trent use a number of indicators to determine a drought period is developing (Severn Trent Water, 2018), including rainfall deficits, soil moisture deficit, low river flows, and falling groundwater levels.

For groundwater, Severn Trent collect national water table and borehole water level data, and analyse them using a time series assessment. Severn Trent does not expect any single low groundwater level in a borehole to trigger significant drought management actions. Instead, a groundwater source will have a minimum reliable output (the deployable output (DO) curve) and any local response drought actions are dictated once this DO curve has been breached. The DO curve approach is also discussed in detail in Misstear et al (2017), where a Deepest Advisable Pumping Level (DAPWL) for a well, beyond which over abstraction will occur, is also discussed.

Without the data from a DO approach, Irish Water tracked our bored well performance by monitoring supply and demand levels. Temporary measures (e.g., tankering) were deployed to address supply short term demand balance deficits. Our demand-side and supply-side actions during the Drought 2018, enabled Irish Water to continue to provide supplies of water to essential national customers, such as farms and hospitals in the rural towns.

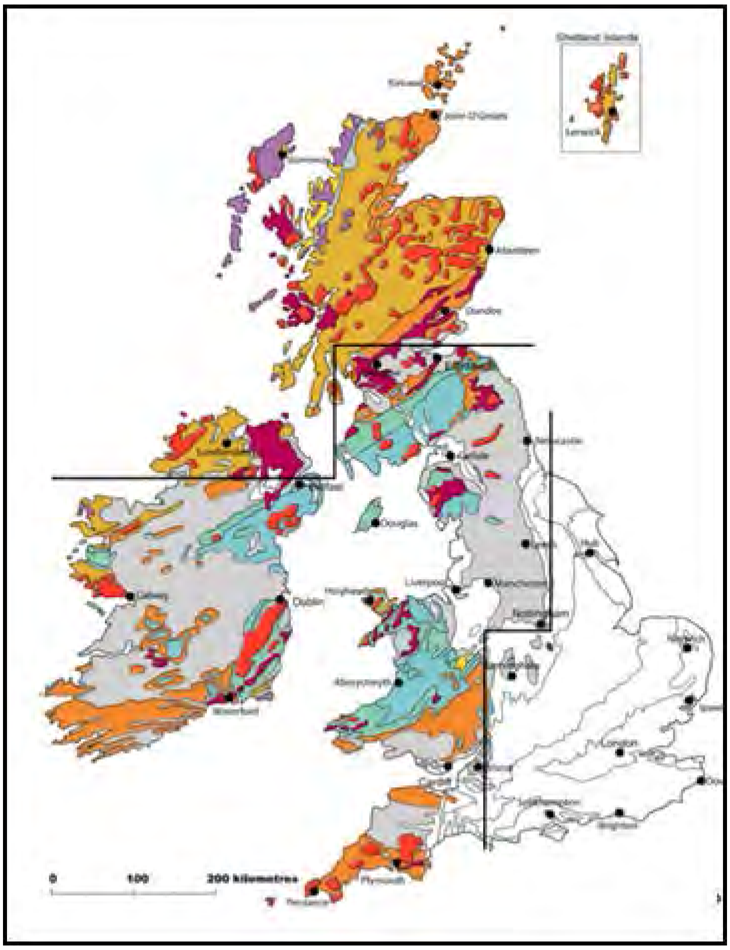

Figure 3. Ireland's Upper Palaeozoic geology is similar to that of the UK, between the black lines, and offers a basis for Irish Water to compare our GW asset organisation to that of midlands England, Wales, and Devon/Cornwall. The Mesozoic geology of UK, is white shading, for illustration purposes only, and the Lower Palaeozoics of Donegal can be associated to Scotland, where both territories are actually groundwater scarce. Much of Severn Trent's remit is to the NE of the Liverpool/Bristol line, while the Leeds/Newcastle line is Yorkshire Water's and Northumbrian's remit.

4. SUPPLY-SIDE ACTIONS AT OUR BOREHOLES

CIRIA Report 137 - *Monitoring, Maintenance and Rehabilitation of Water Supply Boreholes* (CIRIA 1995), informed our approach to managing the programme of works at each borehole, and the supply-side actions we needed to take at the 70 drought stressed groundwater abstractions.

All of the initial borehole call outs were aimed at diagnosing borehole yield and pump performance problems (*CIRIA 137 [Section 2 – Monitoring & Diagnosis])*. Key to a successful diagnosis is an awareness that the borehole abstraction system is composed of four parts:

- Aquifer
- Borehole
- Pump
- Well-head works

IW in collaboration with the Local Authorities initiated a borehole call-out, termed a Hydrogeology Audit, at each borehole going into drought. Checks at the wellhead and borehole required a ruler to measure borehole diameter, a camera for scale pictures at the well head, a dip-meter, and a stopwatch for immediate step-tests. Any decline in operating performance of the Pump was logged by reviewing telemetry on-site, and by interviewing the caretaker regarding questions on changes in discharge rate, discharge head, and energy consumption. Borehole performance checks by step test, included logging discharge rate, rest and pumping water levels, and calculating specific capacity.

Key to determining the condition of the borehole and pump was the use of CCTV cameras, to check downhole casing and screen, for appearance and hydraulic efficiency. In all cases for CCTV, the pump was removed and made safe, where the pump condition was documented for appearance, clogging, abrasion or corrosion. In other cases, where there was known mechanical failure of the pump, specialist electricians/pump suppliers were called in to determine failure reasons and log them for an overnight replacement. More details on the steps taken for a CCTV camera survey at a north Dublin borehole (see Figure 4), and a diagnosis of its malfunction, are set out in Appendix 1.

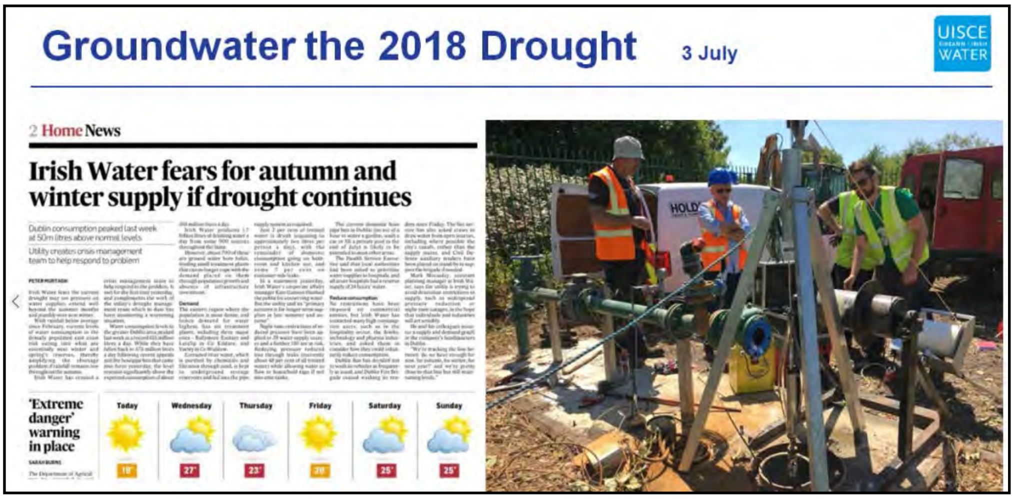

Figure 4. Irish Times 3 July 2018. On the same day we carried out the drought's first camera survey downhole at Bog of the Ring, the Irish Times had recorded the historical drought.

The outputs of the audit were reported onto a standardised Irish Water Audit Report template. Each report has maps, photographs, step-test returns, and recommendations for borehole rehabilitation, abandonment, or borehole replacement. The mix of the supply-side actions and work packages Irish Water commissioned are summarised in Figure 5. In 2019, IW has been undertaking camera surveys, changing pumps, and fixing wellheads into kiosks, as follow-up capital maintenance (CM) fixes, to drought ready our boreholes and extend their operational life at the same time.

Works	Completed
Hydrogeology Audits & Step Tests	73
CCTV Camera Surveys	15
TW – Trial Well	25
PW - Production Well	6
REHAB - Rehabilitation	1

Figure 5. Groundwater Drought Response. Work Package Statistics

5. MAINTENANCE OF GW ASSETS

Irish Water is developing a strategy for the management and maintenance of its 850 GW assets and a key objective will be to minimise any environmental impact of our abstractions. Asset Management decisions will be made on the whole lifecycle of a borehole or spring. Figure 6 identifies the life cycle stages we use in our Asset Management Model, as per the blue shaded 'Lifecycle Delivery Loop'.

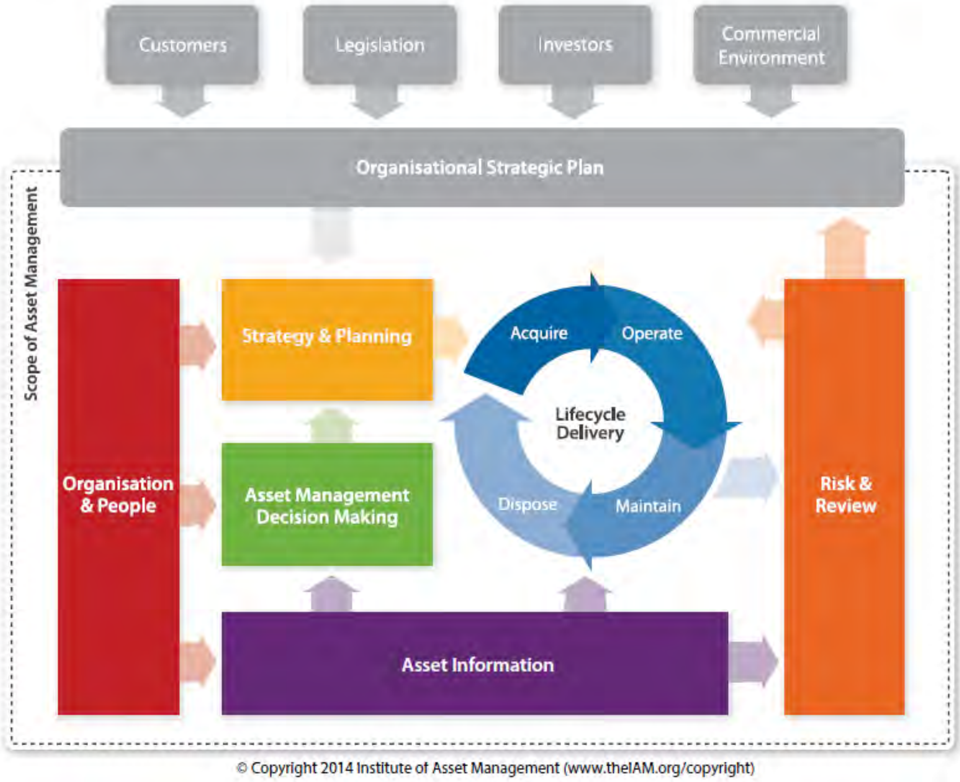

Figure 6. The Asset Management Model (Institute of Asset Management). See blue 'Lifecycle Delivery Loop'.

There are three elements to the Operate/Maintain aspect of the 'Lifecycle Delivery' loop:

i. Inspection, Monitoring;
ii. Preventative Maintenance; and,
iii. Corrective Maintenance.

Implementing these three elements into a Maintenance Programme will enable us to plan the future of our water supply more efficiently. Irish Water wish to construct a more resilient borehole network of G1/G2 boreholes, and engage corrective maintenance on the older G3/G4/G5 boreholes, so that the following business objectives can be met:

- Address Supply Demand Balance deficits;
- Reduce Drinking Water Regulation non-compliances;
- Install and upgrade existing bored wells to meet G1 standards; and
- Provide valuable information to ensure abstractions are sustainable with minimal environmental impact.

ACKNOWLEDGEMENTS

The author wishes to thank all colleagues across Irish Water and Local Authority Partners.

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Misstear, B., Banks, D. & Clark, L. (2017). Water Wells and Boreholes, 2nd edition. Wiley, Chichester, 536 pp. ISBN/ISSN: 978-1-118-95170-5

Severn Trent Water (2018). Draft Drought Plan 2019-2024.

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APPENDIX 1: Monitoring and Maintenance of a Water Supply Well - Bog of the Ring PW 4

The selected borehole lies at the Bog of the Ring (BOTR herein), located in Fingal County Dublin. A review was undertaken of poor performing and out of service assets to address local supply demand balance deficit. An investigation was carried out to determine if returning an existing out of service bored well (PW4) would increase the yield from the well field. Later, aspects of PW4's operational regime were researched, as detailed in Table B1 below (adapted from Tinnelly, 2013):

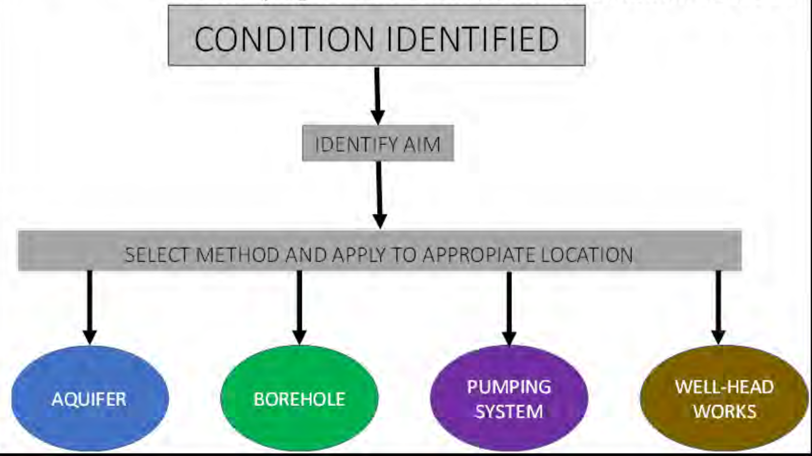
Table B1 BOTR PW4 Borehole Efficiency and Yield Operational

Time Period (mmm-yy)	Pumping Test (if applicable)	Yield (m^3/d)	Comments/ Aquifer Properties/ Water Level trends (Qualitative)
2000	24 hours	850	Reduced to 670 m^3/d after 6 hours into test. Steady-state not reached. Sc = 18.5 m^3/d/m
2000	7 days (Combined PW4+PW5 Abstraction)	594	Drawdown, s = 30.28m Achieved Steady-state. Sc = 19.6 m^3/d/m
May-04 – Feb-05	-	336	Summer recession in water levels, minor recovery in winter
Feb-05 – Mar-06	-	226 - 240	11.9m decline in water levels, not due to increased abstraction. Summer recession in water levels, little recovery in winter
Apr-06 – Jun-06	-	150	Steady-state water levels, no declining trend in water levels
Jul-06 – Dec-06	-	200-230	Declining trend in water levels due to increased abstraction
Dec-06 – Mar-07	-	145	-
Mar-07 – May-07	-	200	-
Jun-07 – May-08	-	146	-
May-08 – Jan-09	-	190	-
Jan-09 – Dec-09	-	150 - 170	-
Jan-10 – Mar 10	-	0	Ceased abstraction at PW4

Data Note Sc = Specific Capacity

Table B1 shows the operation of PW4 was less productive after February 2005, and ceased operation in 2010. The adopted approach to determine the borehole condition was that of CIRIA Report 137 (1995), where the best way to approach a diagnosis and rehabilitation, is to 'match the solution to the problem', as per Figure B1, which we applied to the Aquifer and Borehole parts of the borehole system, by implementing a camera survey downhole:

Figure B1 *Adapted from CIRIA Report 137,*
Identifying a Maintenance or Rehabilitation Method



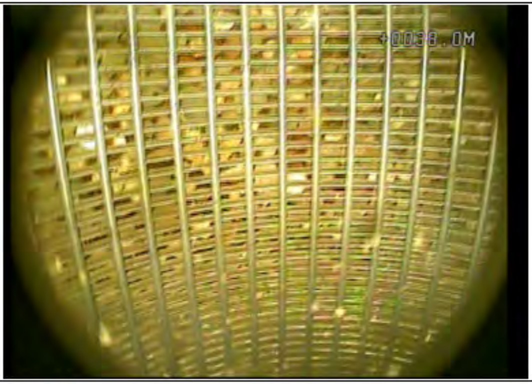
IW attended site on 3rd July 2018, to complete a down-hole CCTV camera survey (CS) to inspect borehole walls, aquifer water entry points, and the pumping system. The pump was pulled, made safe, and examined; details are provided in Table B2 below. Datum for the survey was taken as the top of 10" PVC casing. PW4 was surveyed to a total depth of 89.3 m; the construction of the borehole was plain steel casing from 0 – 36.7 m and a stainless steel screen from 36.7 – 89.3 m. A gravel pack was installed across the screened section. However no further detail was provided to indicate the top of the gravels.

Appendix 1 continued:
All joints were in good condition with the exception of a slight unscrewed joint at 30.7 m (Insert A). The condition of the well screen and gravel pack was noted by the Irish Water to be in excellent condition from 36.7 - 50 m (Insert B). From 50 – 89.3 m, some sediment build up was noted on the screen (Insert C) and an increase in suspended solids within the water column (Insert D). The settlement on slots at a section of the borehole (Insert C) shows little or no flow occurs from the deeper borehole wall.

Table B2 PW4 Pump and Headwork Observations (observed on 03/07/2018)

Information	Data
Static Water Level (mbd)	13.73 m
Pump Depth (mbd)	71 m
Pump Details	Franklin Electric (Submersible Pump) Europa GmbH D-54516 Wittlien 50Hz, 11.0 kW
Rising Main	Lay flat
Electrics	Electricity ESB Phase 3 blown. Only 2 phases in operation. i.e. Electrical Failure

Mbd = metres below datum; datum = Top of 10" PVC casing

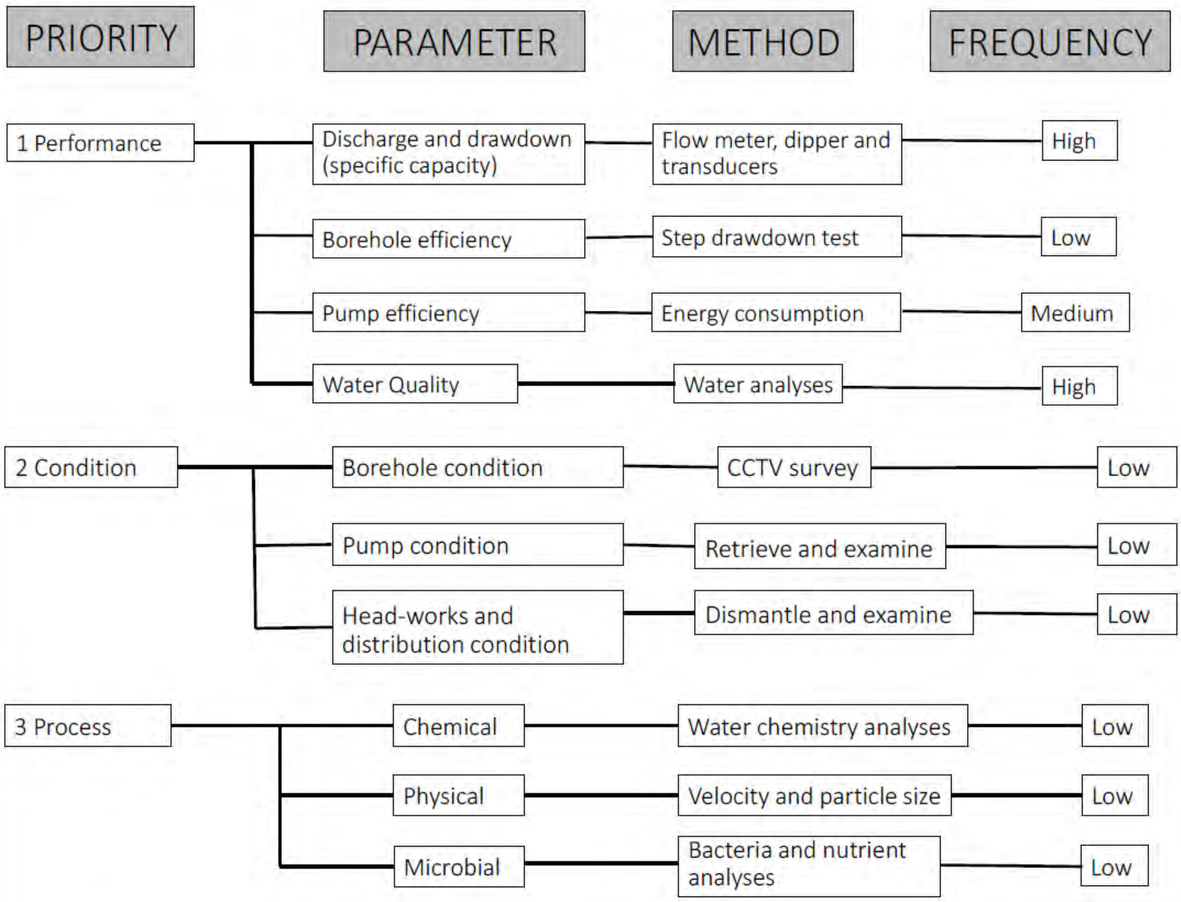
Insert A *Adapted from JS Remediation (2018), joint in plain steel casing, slightly unscrewed at 30.7 m*	Insert B *Adapted from JS Remediation (2018), screen clear with gravel pack visible at 38 m*
	
Insert C *Adapted from JS Remediation (2018), build-up of sediment on screen at 50.9 m*	Insert D *Adapted from JS Remediation (2018), joint in screen section and reduction in visibility due to increased suspended particles within water column*
	

Tinnelly in 2000, while drilling, logged deepest inflows at 44-46 m depth, yet we see the screened section is from 36.7 – 89.3 m. After drilling, steady state pumping on Day 7 of the Constant Pumping Test was achieved at 30.3 m PWL, suggesting good storage in the bedrock Limestone aquifer.
The CCTV camera survey enabled a diagnosis of deposits on screen slots was likely due to an inactive well and deposits collecting in stagnant deeper sections, where there is no flow in the rock wall. Wear and tear of pump with a phase malfunction was the likely cause of failure. In March 2019, the Local Authority installed a replacement pump after electrical phase repair, and achieved the pumping and supply of 1.5 MLD raw water into the network. The monitoring/assessment/audit approach at a borehole will differ for every site, as will frequency of checks. The key CIRIA table for considering the audit type at a borehole, is presented in Figure B2, Appendix 2.

Appendix: Figure B2

GUIDELINES FOR MONITORING OF BOREHOLES

Adapted from CIRIA Report 137



Priority

1 : Essential

2 : Strongly recommended

3 : Recommended

Frequency

High : Daily to monthly

Medium : Monthly to every 6 months

Low : 6 monthly to every 5 years

REALIGNMENT OF WELLFIELD OPERATIONS AND WELL REHABILITATION NEEDS AT THE BENNETTSBRIDGE PUBLIC WATER SUPPLY

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1. INTRODUCTION

In response to the 2018 drought conditions, Irish Water mobilized resources to assess and address water supply shortfalls across the country. The responses addressed immediate shortfalls but also longer-term planning aimed at reducing potential impacts of similar conditions in the future. The former consisted of supply augmentation through trial well drilling and pumping. The latter examined vulnerabilities of supply at individual sources and finding ways to enhance or optimize water supply operations. This work is ongoing as part of Irish Water's broader asset planning.

The current paper provides an outline of activities being undertaken at the Bennettsbridge public water supply (PWS) located approximately 4 km northwest of Thomastown, Co. Kilkenny (Figure 1), adjacent to the River Nore. Being the main source of water for towns and farms in the immediate region, the PWS was under severe strain during the summer of 2018 when average total water demands exceeded the capacity of water supply from the existing PWS.

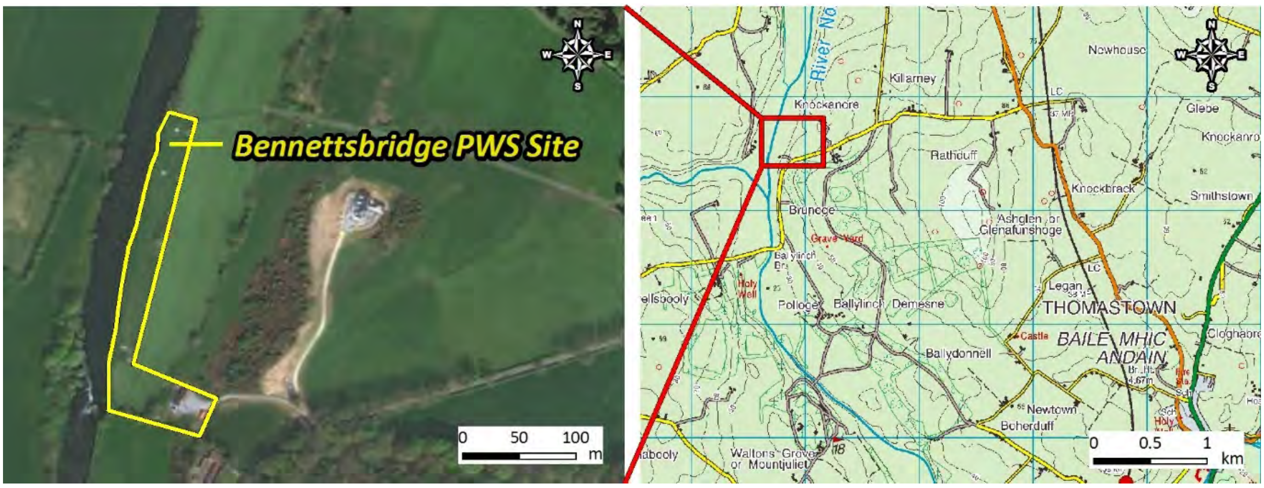


Figure 1: Bennettsbridge PWS Location

2. OVERVIEW OF THE PWS

The PWS sources groundwater from four wells and an infiltration gallery which deliver water to the Bennettsbridge Water Treatment Plant (WTP) (Figure 2). One existing well, BH5 at the northern end of the site, is idle (abandoned). Well BH101 (or BH3) was drilled, tested and pumped in July 2018 as an emergency measure and was placed into full production in October 2018 to augment the supply.

Individual well depths range from approximately 50 to 100 m below ground level (mBGL). Pumps are installed between 39 and 80 mBGL. Each well is completed in, and mainly pump groundwater from, the Ballysteen (Limestone) Formation, in which dolomitized units represent the main aquifer units. These are classified by Geological Survey Ireland as "Ll", i.e., locally important bedrock aquifer which is "*moderately productive only in local zones*". Well construction information indicates that some of the wells also draw groundwater from shallow alluvial sand and gravel sediments that are associated with the adjacent River Nore.

Figure 2: Main Components of the Bennettsbridge PWS

In the emergency context, trial well BH101 was constructed specifically to exploit the transition zone which marks the contact between subsoils and bedrock. In BH101, shallow sand and gravel deposits are separated from the bedrock by glacial till which is approximately 5 m thick. The trial well work provided site information on depth to bedrock, lithologies, geological contact depths, presence of fracture zones, signs of weathering and driller's estimation of potential yield. The well was also test pumped and sampled.

The infiltration gallery runs parallel to the river, approximately 30 m from the river, and passively draws groundwater from sand and gravel-grade sediments approximately 2.5 m below the elevation of the river bed. The infiltration gallery was constructed in the 1960s and knowledge about below-ground construction details and its general performance (seasonal, longer-term) is poor.

The River Nore and immediate floodplain areas is a designated Special Area of Conservation. Hence, the hydraulic interaction between the bedrock and alluvial aquifer units and the river is of interest in the general assessment of wellfield operations. A conceptual diagram of the relationship between the river, infiltration gallery and production well(s) is presented in Figure 3.

As summarized in Table 1, total average groundwater production in June 2018 was 2,944 m^3/d, the total water demand was 3,300 m^3/d and the shortfall in supply was defined as 356 m^3/d. The new well BH101 currently produces an average of 35 m^3/hr or 840 m^3/d. This implies that the June 2018 deficit has been closed and that there is a theoretical surplus in wellfield capacity of approximately 480 m^3/d. However, production from the infiltration gallery is vulnerable to river levels and questions about potential well interference have arisen which may yet constrain longer-term production, especially under drought scenarios.

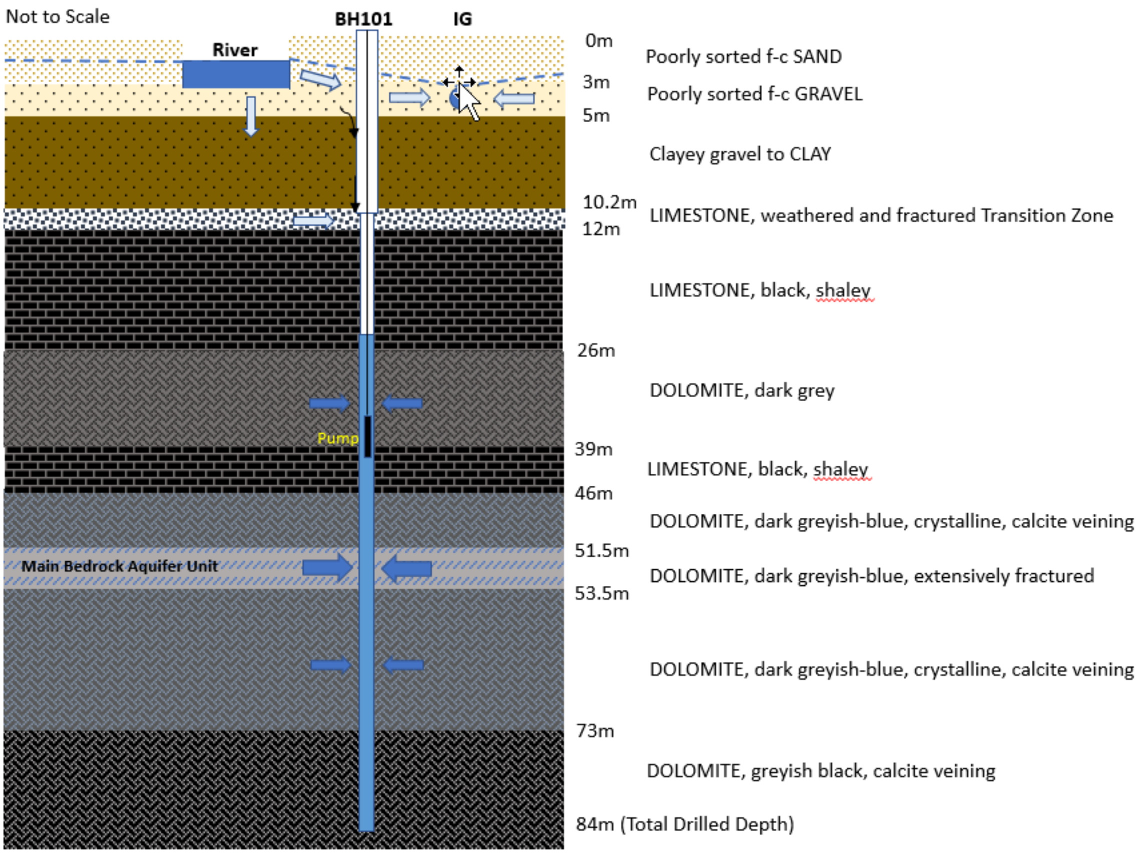


Figure 3: Sketch of the groundwater flow systems at Bennettsbridge PWS

Table 1: Summary of Water Production and Water Balance

Item	Production m^3/hr June 2018	Production m^3/d June 2018
BH1	18	432
BH2	24	576
BH4	42	1,008
Infiltration Gallery	39	928
Water Balance	**m^3/hr**	**m^3/d**
Total Supply Capacity June 2018	123	2,944
Estimated Demand June 2018	138	3,300
Estimated Deficit June 2018	15	356
Additional Production from Well BH101 (BH3)	35	840
Total Supply Capacity October 2018	158	4,140
Theoretical Current Surplus	20	840

3. ASSESSMENT OBJECTIVES

For the reasons described above, Irish Water is undertaking an operational “realignment assessment” of the wellfield which is aimed at:

- Examining how production pumping may be optimized with regards to operational efficiency;
- Exploring the additional capacity that may be gained by improved/adjusted well operations;
- Defining pumping rates that can be maintained under prolonged dry weather conditions; and

- Evaluating the additional wellfield capacity that may be needed to meet future water demands under both “normal” seasonal conditions as well as the “next drought”.

In the case of the Bennettsbridge PWS, a stated aim of Irish Water is also to plan for a sustainable groundwater supply which does not rely on the infiltration gallery.

4. APPROACH

The realignment assessment has to consider both the wellfield facilities (notably the wells and infiltration gallery), the groundwater resource (exploited aquifer units) and potential environmental effects of expanded groundwater production (notably on the baseflow of the River Nore, especially during drought conditions).

Irish Water is using the framework described in the CIRIA Report 137 (Monitoring, maintenance and rehabilitation of water supply boreholes) as a programmatic guide for trouble-shooting their groundwater-sourced water supplies. This guide is one of many that highlights the need to evaluate well and wellfield performance against other supply components such as reservoirs, pipelines, system controls (e.g., level switches), booster pumps, and valves.

In the context of well performance and decreasing well yields over time especially, an updated approach for borehole diagnostics was also developed under the drought mitigation initiatives by Irish Water. Summarized in Figure 4, the approach involves an initial desk-based assessment of potential issues which is followed up by site- or well-specific checks and investigation. In broad terms, the steps involved are:

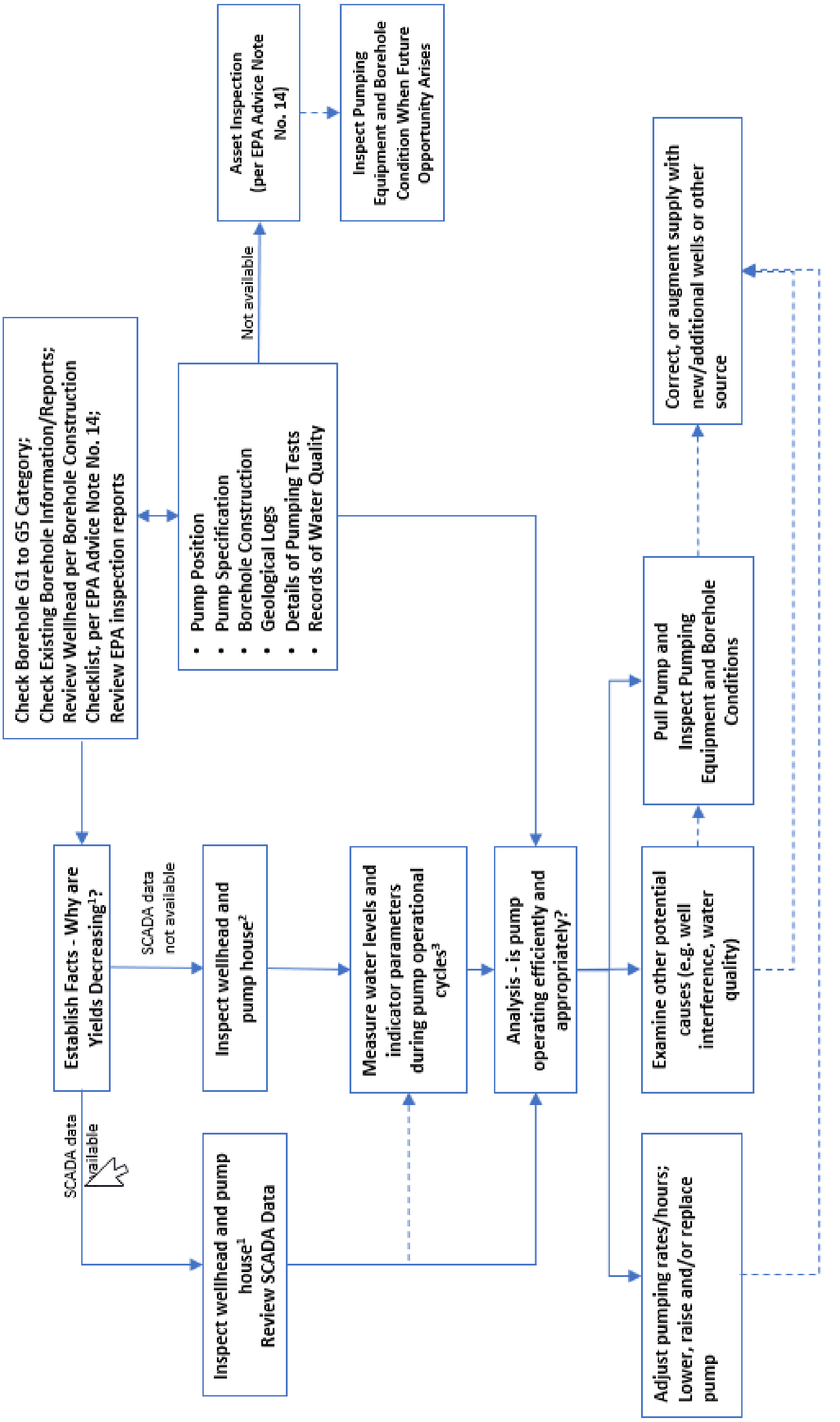
- Initially, to check the power supply to the site and the submersible pump by following sets of diagnostic steps that are tailored for the asset/installation, including the functionality of motor control panels and switchgear. At this stage, the details of diagnostic steps should be prepared by, and possibly also conducted by, a qualified electrical engineer;

- Subsequently, to check the physical integrity of above-ground installations to ascertain that there are no above-ground leaks or blockages; and

- Finally (or in parallel), proceed with the desk-based review of the borehole installation and site operational data – including discharge rates, pumping water levels and water quality.

The first step in the desk-based assessment approach is to collate and review the existing information that is available for the well. The checklists that are included in the EPA Advice Note No. 14 (Borehole Construction and Wellhead Protection) is particularly useful in this regard and may also be used to guide the physical inspections at the site. The outcome of the assessment is a set of steps or recommendations for further action. The desk-study also takes into consideration the G1 to G5 borehole classification and the associated source protection needs and treatment requirements.

In all circumstances, the desk-based review, which includes operational data, is an important part of the diagnostics. Decreasing well yields and certain types of water quality problems (e.g., turbidity) in borehole supplies can be influenced by how the borehole was constructed and how the pumping system operates. Many public supply boreholes are equipped with submersible pumps that are capable of pumping more than tested or recommended well yields, and quite often the pump sits in the wrong place at the bottom of G3 to G5 boreholes, habitually in fines at the bottom of a well (which can be a source of turbidity). Pumping beyond what a well can sustain results in rapid lowering of groundwater levels and often frequent on/off cycling of the pumping unit, which is manifested by rapidly oscillating water levels in the well. This is inefficient pumping which reduces life-spans of pumping units and contributes to higher-than-necessary O&M costs.



¹ In parallel, or subsequent to, establish if problem may be related to electro-mechanical issues at surface – e.g. pipe/valve leaks, power supply.
² Per Appendix 1 of EPA Advice Note No. 14.
³ Min. 24 hours.

Figure 4: General Approach for Borehole Diagnostics

Irish Water boreholes are classified as G1 to G5. All ‘G’ Boreholes consist of both surface and subsurface installations. Surface installations can be inspected and tested at the surface. Submersible pumps can also be diagnosed and tested at the surface but can only be inspected and verified after pumping equipment is pulled from the borehole. Thus, downhole conditions in the borehole can also only be inspected after pumping equipment is removed and a downhole camera survey or geophysical logging (e.g., acoustic televiewer) is carried out.

5. OPERATIONAL REALIGNMENT – PROGRAMME OF WORKS

The programme of works for the realignment assessment of the Bennettsbridge PWS consists of the following elements which are either ongoing, planned and/or recommended.

1. Installation of monitoring equipment on each major component of the PWS. To date, pressure transducers have been installed to automatically record: a) groundwater levels in each of the wells; b) water levels in the main sump that transmits groundwater from the infiltration gallery (via gravity) to the WTP; and c) water levels in the River Nore. Furthermore, each discharge pipe has been equipped with flowmeters to record pumping rates. The data are stored and accessible for viewing and downloads on a web-based platform.
2. Conducting downhole camera surveys of each well. To date, BH101 and the abandoned well at the northern end of the site have been surveyed. The remaining wells will be surveyed when pumps are pulled in the future. The surveys will confirm the construction details and physical integrity of each well. Based on the surveys, recommendations for potential well rehabilitation activity will be made.
3. Inspection of pumps and riser mains for damage, general wear and tear, and possible features which may affect pumping efficiency – e.g. biofilm or sediment clogging of pump intake screens.
4. Potentially, conducting well rehabilitation activity in each well (e.g. chemical cleaning, surging), depending on findings from the camera survey and inspection of the equipment removed from the wells.
5. Replacements of current submersible pumps to variable speed pumps.
6. Conducting step drawdown testing of each existing and/or rehabilitated well.

The operational groundwater data (pumping rates and water levels) will be assessed in context of:

a) Pumping efficiencies
b) Interference effects between wells and the infiltration gallery
c) Suitability of the installed pumps (e.g., against duty points of pumps; benefits of variable speed drives)
d) River baseflow diversions from the wellfield pumping, especially during low flow conditions
e) Capacity to expand wellfield pumping to meet projected (and experienced) demands during drought conditions
f) Feasibility of replacing the infiltration gallery with expanded well pumping (new or existing wells).

In addition to the purely hydrogeological aspects of the assessment, the engineering of expanded wellfield operations also has to be considered. For example, currently used riser mains are nominal 75 or 100 mm in diameter. The riser mains from BH2, BH101 (or BH3) and BH4 connect to a common transmission main to the WTP which is nominal 150 mm in diameter and approximately 250 m long. Although the elevation and head difference across the wellfield is less than 6 m, potential increased production rates in the future would lead to increases in friction and head losses in the system, which the currently installed pumps would have to manage and/or a new pump selection would have to be considered. Therefore, the overall realignment assessment requires the combined and coordinated inputs of electro-mechanical engineers and hydrogeologists.

6. PRELIMINARY FINDINGS

The assessment is ongoing. Preliminary findings demonstrate that well construction and pumping rates affect turbidity, which has been an ongoing issue requiring water treatment at the Bennettsbridge PWS. This is exemplified in Figure 5 which shows turbidity improvements at reduced pumping rates during the test pumping of trial well BH101. The turbidity is likely caused by water ingress from the transition zone and/or shallow sand and gravel sediments, whereby high in-well flow velocities result in turbulent flow conditions and sediment transport. Wells can be re-designed and re-installed to lessen such effects, at cost. Alternatively, pumping rates from each well may be reduced, but this implies an operational realignment that involves additional wells across a broader area in order to meet water demands. This option is not practical and is not cost effective compared to treatment at the WTP.

Figure 5: Turbid water at 47 m^3/hr (left); sediment-free water at 21 m^3/hr (right)

With regards to treatment, iron and manganese concentrations are elevated and may contribute to potential clogging of screens and pump intakes (e.g., biofilms) inside the boreholes. This is subject to further assessment, and concentrations are not atypical of what is observed in other water supplies that source water from similar aquifer types.

The River Nore is unaffected by the pumping of the wellfield or Infiltration Gallery (IG). The nearest upstream gauge is 12 km away at John's Bridge in Kilkenny where the 95-percentile flow (Q_{95}) is 3.67 m^3/s. The current total supply capacity of the wellfield and IG is 4,140 m^3/d, or 0.048 m^3/s. This represents 1.3% of the Q_{95} flow John's Bridge. The diversion of water from the river to the wellfield is less since only a fraction of the groundwater that is pumped is sourced from the river. Accordingly, the River Nore is largely unaffected by the Bennettsbridge PWS pumping.

As shown in Figure 6, water levels in the River Nore affect water levels along the IG as measured in an IG collector sump. However, the water levels in the IG sump also show drawdown and recovery cycles, which can be linked to pumping operations of both the wells and the IG. All groundwater pumping operations at the site are controlled by a level switch at the WTP which turns pumps on/off in unison or as set by the operators.

Figure 7 shows the water levels in the IG sump and production well BH2 between 11 January and 14 February 2019. During this period, BH2 was idle between 11 January and 4 February 2019, yet shows the same drawdown and recovery cycles as the IG. This suggests that BH2 may be influenced by the operations of the IG. However, the other production wells may also have influenced water levels in BH2. When BH2 began pumping on 4 February 2019, the drawdown effect in this well is clearly depicted, but the magnitude of drawdown and recovery in the IG remains unchanged. Thus, it is possible that the initial drawdown/recovery cycles in BH2 prior to 4 February 2019 reflects the pumping in the other wells rather than the IG. It also leaves the possibility that the hydraulic connection between the deeper wells and the IG is limited. To fully understand relative influences of pumping and potential well interferences, longer-term monitoring is needed and clarification of hydraulic relationships will require further testing of the different wells and IG operating independently. This is recommended and planned.

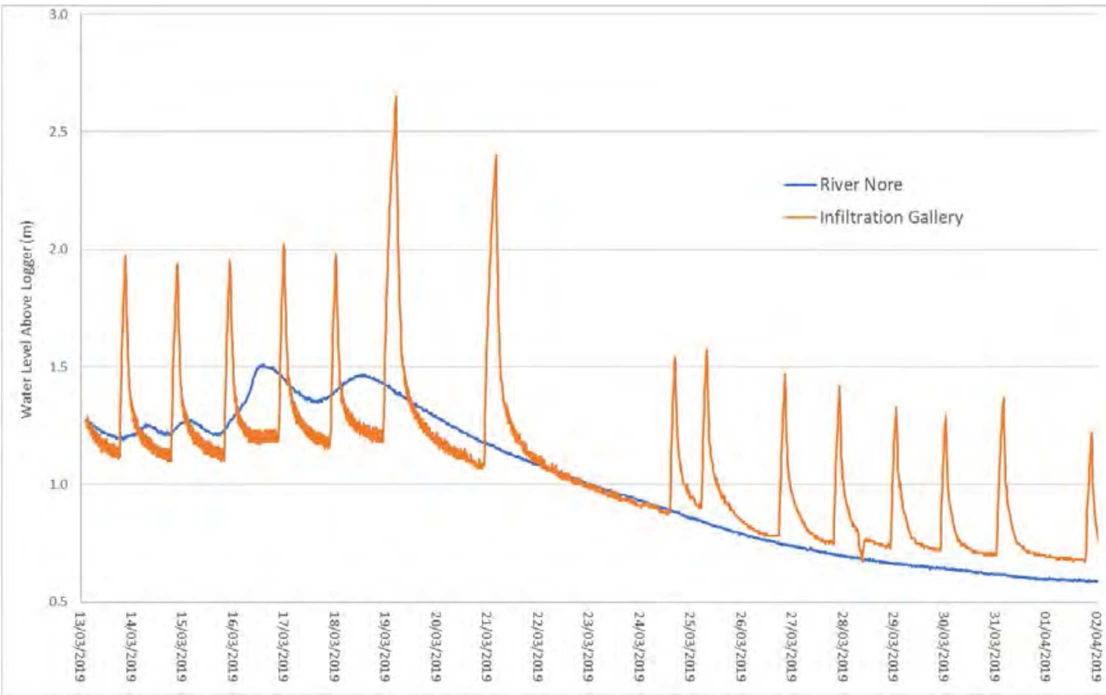


Figure 6: Water Levels in the River Nore and Infiltration Gallery

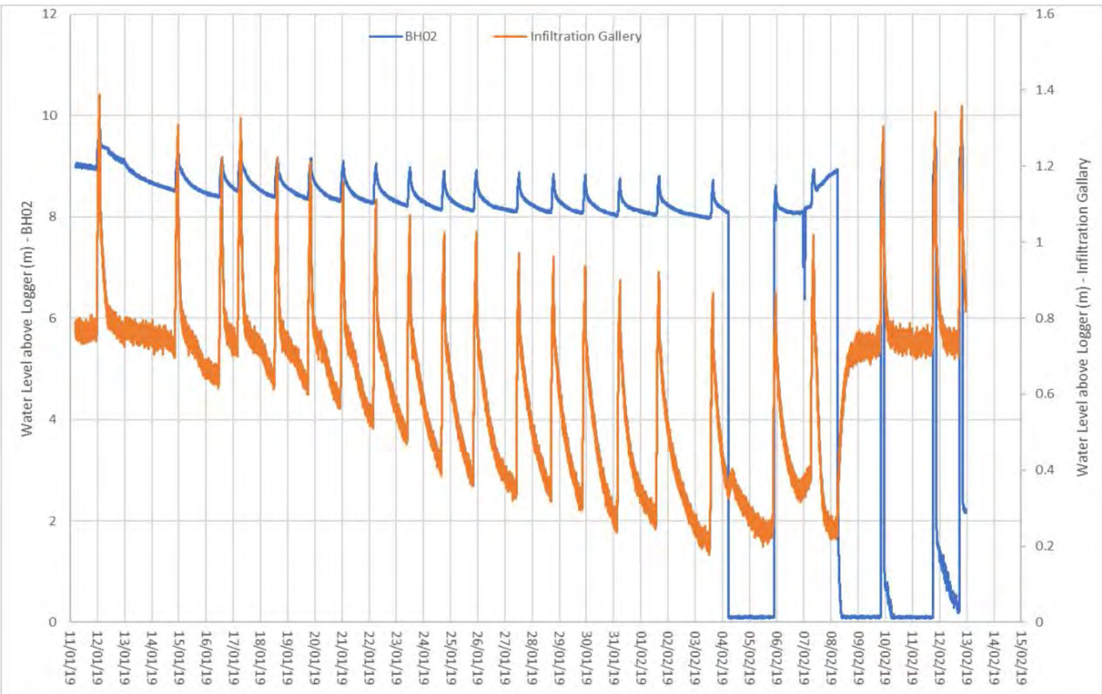


Figure 7: Water Levels in the Infiltration Gallery and BH02 (note, the logger in BH2 ran dry when BH2 began pumping and has since been redeployed deeper in the well)

7. CONCLUSION

The ongoing work at the Bennettsbridge PWS will provide monitoring-based data which will help inform decisions about possible realignment of wellfield operations, well rehabilitation needs and pump selection. The realignment has short-term (drought mitigation) and longer-term (efficiency) goals. Moreover, under a future scenario in which the IG may be decommissioned, the assessment will provide guidance on potential requirements for wellfield expansion to meet projected water demands.

The current assessment is guided by the framework described in the CIRIA Report 137 (Monitoring, maintenance and rehabilitation of water supply boreholes) as well as updated guidance on borehole diagnostics developed for Irish Water under the drought mitigation initiative in 2018. As such, the experiences gained at the Bennettsbridge PWS will be used to inform a wider assessment of other wellfields across the country to deliver programmes of wellfield operations which address questions about water supply sustainability, operational efficiency, supply resilience and treatment needs.

THE ROLE OF G1 WELL DESIGN IN THE OPERATION AND MAINTENANCE OF A RESILIENT GROUNDWATER SUPPLY

Gerry Baker

Arup

ABSTRACT

There is now ample guidance and advice available to support the development of high quality groundwater supplies in Ireland. Irish Water have adopted these designs as their G1 production well classification and proposed that wells constructed to the EPA Advice Note 14 only require chlorination. This offers major reduction in operation and treatment costs when compared to supply requirements for surface water sites or less well protected groundwater supplies.

A paradigm shift is required for the sustainable development of groundwater supplies from a focus on a single borehole solution for each individual site to having multiple wells constructed to G1 status abstracting at lower rates to provide better quality water, with lower treatment requirements, lower pumping costs and more resilience to drought when it occurs. This will lead to a more mature and sustainable management of our groundwater resources and assets.

INTRODUCTION

There has been a limited amount of public groundwater supply development in the past ten years in Ireland. The collapse of the housing market in Ireland and the Global Financial Crisis (GFC) in 2008 limited the availability of public funding for infrastructure projects in the subsequent years. Up to that point public groundwater supplies in Ireland were commissioned through the local authorities. In the years leading up to 2008 there was a strong level of activity in the sector to keep up with the rapidly growing housing stock and population increase. With the establishment of Irish Water in 2013 the responsibility for developing new supplies shifted from the local authorities to Irish Water. There followed a period of gestation where there was limited advancement of groundwater supplies.

Irish Water has now started to progress groundwater supply development. This has increased since the inception of the Multi-Supplier Frameworks for Consulting Hydrogeologists and Water Well Drillers which allows for more efficient tendering of the work. The onset of the drought in 2018 clearly highlighted the vulnerability of the groundwater and surface water supplies and this provided a further impetus.

2018 DROUGHT IMPACT ON GROUNDWATER

The 2018 drought appeared to have a significant impact on the groundwater and surface water resources in the south west of the country, but even more specifically in North County Cork and County Limerick. Groundwater supplies in Kerry were not as significantly impacted. A review of the Soil Moisture Deficit (SMD) data from Met Eireann for Moore Park (North Cork) shows a significantly higher SMD for this period (70mm) than the average historic level 25mm, see Figure 1.

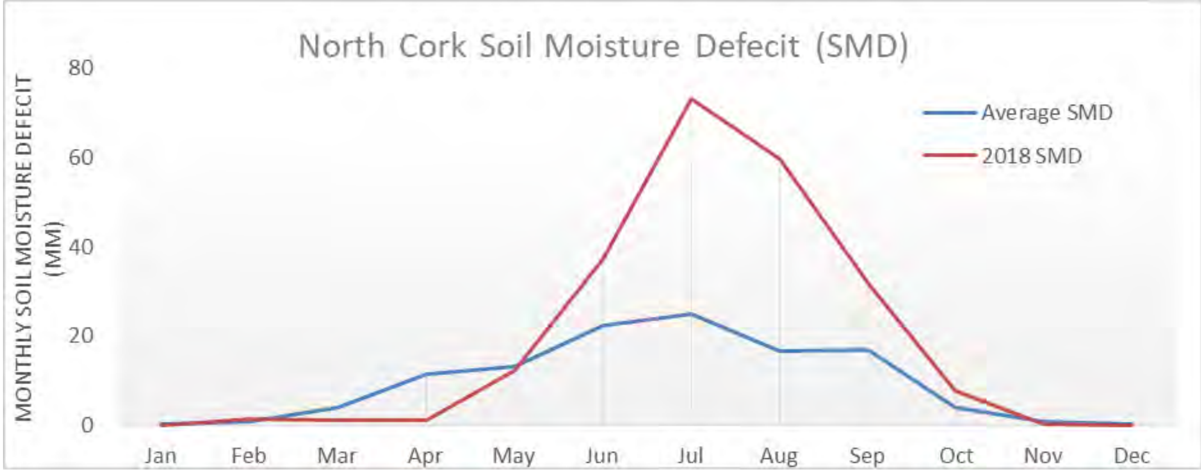


Figure 1: Soil Moisture Deficit (SMD) at Moore Park, Co Cork.

The EPA Groundwater Level Monitoring Network in this region is relatively limited with only three monitoring locations (Taur GWS, Flesk and Dripsey) covering the majority Cork, Kerry and Limerick. The results from the Taur site were not available for the drought. A review of the available data for the other sites shows the groundwater levels reduced to new minima (i.e. new 0^{th} Percentile) and in the case of the Dripsey Catchment in North Cork stayed at that level for an extended period of time, see Figure 2.

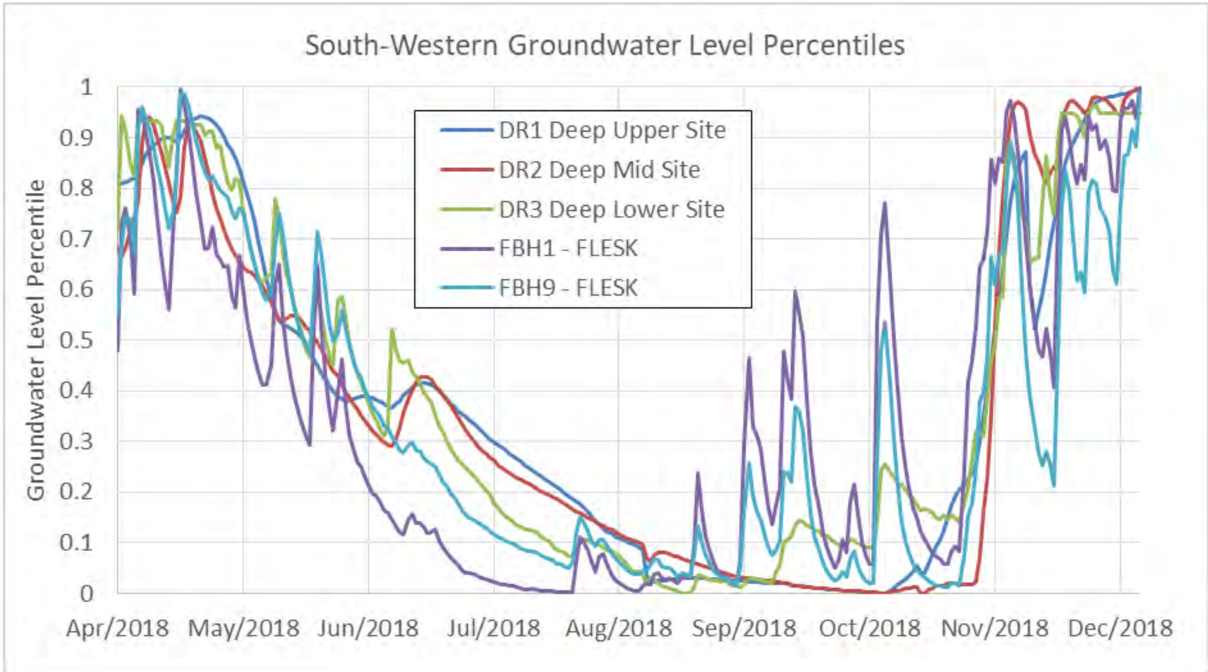


Figure 2: Groundwater Level Percentiles in Cork & Kerry During the 2018 Drought

IRISH WATER DROUGHT RESPONSE

The Arup hydrogeology team was commissioned to assist Irish Water with the drought response for the Counties of Limerick, Cork and Kerry. Prior to this, Arup were also commissioned to assist with the development of 14 Trial wells which also happened to be mainly in the south west.

The first step in the drought works was a site audit including site visits at locations experiencing supply issues such as night-time supply restrictions or where there was tanking on-going. The site visits included a meeting with local Irish Water and Local Authority staff. The common finding for many of the sites, particularly the smaller groundwater supplies was:

- Limited information available at the site on the well.
- Caretaker had limited knowledge of borehole construction.
- No dip tube available to monitor groundwater levels at the site.
- Wells typically had a low-level conductivity sensor to ensure pump did not dry out.
- Pumps typically had a variable speed drive installed to allow adjustment of pumping rate.
- Discharge monitoring and turbidity monitoring were generally available at most sites.

The results suggest the following actions are required for many of the sites:

- Literature search at the local authority offices to find hard copy hydrogeology report on the well completed at the time or drillers log.
- Retraction of the pump and completion of pump maintenance and borehole camera survey
- Installation of groundwater level loggers and a dip tube when pumps are being reinstalled.
- Provision of a Hydrogeological Information Sheet for posting on the notice board in the pump house or a bound copy of a Hydrogeologists Report to be provided in the pump house.

The drought response programme in the south-west included the drilling of trial wells at the following locations:

- Co. Limerick: Croom Bypass, Croom Reservoir, Croom Skagh, Glin, Kilcoleman, Oola, Pallasgreen.
- Co. Kerry: Annascaul, Aughacasla, Emlaghpaste, Cahersiveen.
- Co. Cork: Ballinatona, Charleville.

THE G1 PRODUCTION WELL DESIGN

Irish Water has developed a new system for the classification of its groundwater supply assets (wells and springs). The G1 to G5 system aligns with the treatment requirements of surface water supplies which range from S1 to S5. This classification system is outlined in the Irish Water Guidelines (Ball 2017) and a detailed description of the system was presented at the 2018 IAH Conference (Ball 2018).

The highest classification is a G1 borehole which requires only the first level of treatment i.e. the addition of chlorine to the water. This is not a treatment to cure an inherent problem with the raw water, but more the addition of chlorine as a preservative to protect the water as it passes through the distribution system to the consumer. Irish Water have accepted the standard and guidelines provided in the EPA Advice Note 14 *Borehole Construction and Wellhead Protection* (EPA 2013), which includes the Institute of Geologists of Ireland’s *Water Well Guidelines* (IGI 2007). Both guidelines present a clear graphical representation of the ideal finished water well in bedrock and sand and gravel aquifers as shown in Figure 3.

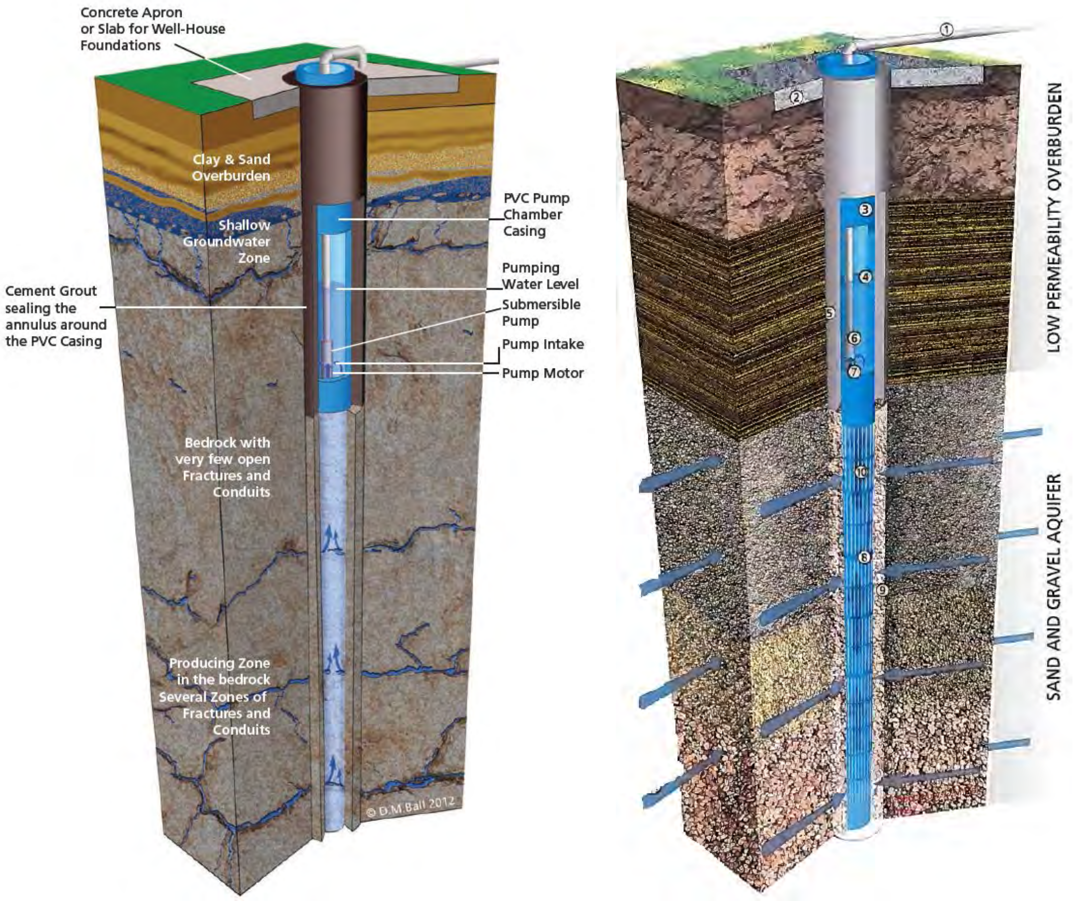


Figure 3: G1 Well Design for Bedrock and Sand and Gravel Aquifers

The key features in the G1 Well Design are as follows:

- Designed and supervised by a hydrogeologist in accordance with EPA 2013,
- PVC pump chamber casing with a complete cement grout seal,
- Pump in correct position inside pump chamber casing,
- Water flows in and up from the deep groundwater system,
- Shallow groundwater is excluded by pump camber casing and grout,
- Pump operated continuously or for long pumping cycles,
- Pump motor cooled by groundwater flowing up to the pump intake.

PARADIGN SHIFT: BOREHOLE *Vs* ASSET *Vs* RESOUCE

The G1 design includes the counter intuitive approach of grouting out potential inflows to the well and possibly reducing well yield! This could explain the resistance to move in this direction by some. The mindset for groundwater supply development in the past was focused to the borehole, as this is the object that is being paid for and constructed. Therefore, the tendency is to abstract as much as possible from that borehole to get the best value for money with the first formula shown in Table 1. This sets out an example of developing a groundwater supply to serve 1,000m^3/d in a limestone aquifer with about one quarter of the flow coming from the top 30m.

Table 1: Groundwater Supply Value Statements – Hypothetical Order of Magnitude Example

Scenario	BH Type	Drilling Cost	Hydrogeologist	Treatment	Yield	Cost / m3
BH Only	G2/3	€ 15,000			1,000	€15
	G1	€ 35,000	€ 10,000		750	€60
	2xG1	€ 70,000	€ 15,000		1,000	€85
Including Treatment	G2/3	€ 15,000		€3,500,000	€ 1,000	€3,515
	G1	€ 35,000	€ 10,000	€ 25,000	750	€93
	2xG1	€ 70,000	€ 15,000	€ 25,000	1,000	€110

The cost for the G2 or G3 well is just the directly commissioned cost of the drilling which could be approximately €15,000 which results in a capital cost per metre cube per day of €15. With a G1 design there is the additional cost of a hydrogeologist for well design, drilling supervision and reporting. The cost of drilling increases as we now have wider diameters and two days standing time while the grout is setting before the production section can be drilled.

As the G1 has grouted out a quarter of the flow the well yield is now only to 750 m^3/d and so the cost is €60 m^3. This is four times the price!! Furthermore, as the demand is still 1,000m^3/d so then a second production well must be drilled and now the value statement becomes: cost increases further to €85/m^3. Which is now near six times the cost!!

However, we need to broaden this value proposition to consider the cost of treatment. If the wells are not drilled to G1 standard, then they could require a more expensive treatment such as a cryptosporidium and Trihalomethane (THM) barrier and the costs start into six figure sums quite easily. For example the recent upgrade at Kenmare, which supplies 1,300m^3/d, was €4,500,000 (https://www.water.ie/projects-plans/our-projects/kenmare-water-supply-sche/). This is shown in the second set of value statements in Table 1 and now the true cost of poorly constructed boreholes becomes apparent!

This mindset of getting value from each individual borehole leads to the tendency to place the pump at the base of the borehole and pump as much as possible from the well. This again feeds into the original formula as the more you can get out of one well the more value you get from it, right? However, when we shift our perspective from the well to the aquifer this changes the value proposition again.

Over abstracting wells is also bad value for money when well hydraulics are considered. The well efficiency of a borehole will reduce with increasing abstraction (Misstear *et al* 2017). Therefore, the pump is drawing water from a significant depth even though the drawdown in the aquifer is only perhaps 20% of the total drawdown. A typical step test analysis chart is shown in Figure 5 (Baker 2009) which shows that beyond a certain point the well will become unsustainable.

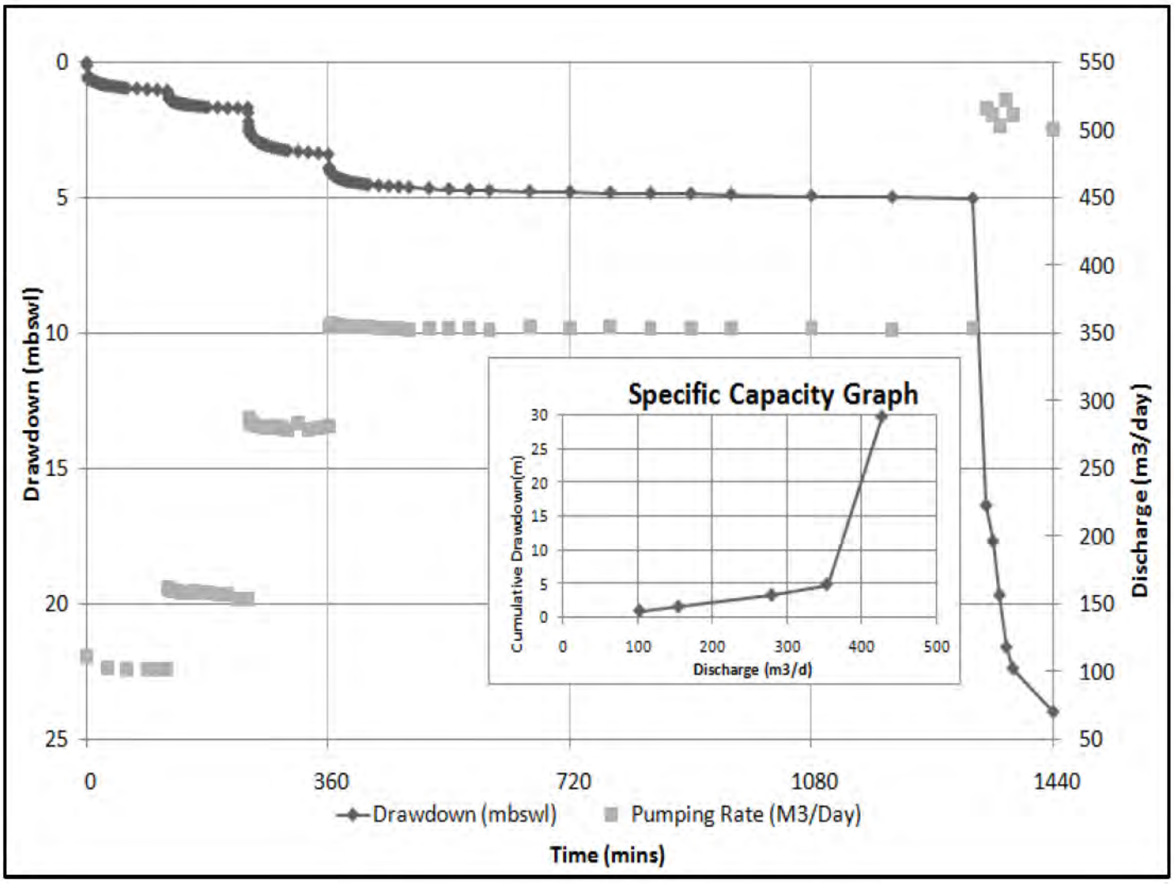


Figure 4: Combined Step Test and Specific Capacity Chart

When the pump is at the base of the well and the water level is continually drawn down to 70mbgl there is no resilience to reducing aquifer storage during times of drought. Therefore, when this well dries up during a drought it is then necessary to tanker water from other regional supplies to maintain supply. This has a significant cost associated with it which can be up to €1,500/day for a 20m^3 tanker. This also puts further pressure on other supplies which are supplying the tanker.

If the yield from our hypothetical 1,000m^3/d supply reduced by half we would therefore require 25 tanker delivers a day to keep up. Presuming the time to fill the tanker, complete the trip from the regional source, discharge the tanker and return back took one hour this is perhaps a total of 10 deliveries per truck/driver. Therefore probably at least two trucks are required concurrently. An extended period of tanking of perhaps 2 weeks to keep the supply going therefore represents an additional unbudgeted cost of €42,000; for which we could have had the extra well drilled!

Additional wells abstracting at a lower average rate results in a higher well efficiency and less dramatic drawdown across the aquifer. If an over abstracted well field is allowed to recover during winter this allow the storage to fill back up. If it is then pumped at a lower rate across more wells it leaves some storage in the *bank* to allow the aquifer and well to be temporarily drawn down in times of drought. This is similar to have a nest egg you can dip into rather than continually running a constant overdraft.

Other benefits of pumping at lower rates across more wells includes having a duty and standby arrangement whereby if there is a pump failure for some reason the other wells can take the load without a catastrophic disruption in supply. Pumping at high rates and low well efficiencies also gives rise to turbulent flow in the well which leads to issues with iron and manganese.

A review of pump rating curves also clearly shows how pump efficiency can easily reduce by 50% when drawing from 80m as opposed to 40m. Therefore, the running costs of having two pumps with half the drawdown can be the same as one well with twice the drawdown.

NEW G1 WELLS IN COUNTY LIMERICK

Arup was involved in the completion of two new G1 production wells which were drilled in Croom and Adare in Co. Limerick recently. Both sites had pre-existing wells in production and therefore there was some baseline knowledge with which to base the production well design upon. The Croom site is mapped within a narrow outcrop of the Ballysteen formation set amongst the Waulsortian Limestones. The Ballysteen is a dark muddy limestone and shale that is classified as a locally important aquifer, whereas the drilling results were more indicative of the pale grey massive limestones of the Waulsortian formation which is a regionally important aquifer. The Adare site is also mapped within the Waulsortian Limestone and this is reflective of the bedrock encountered on site.

The existing wells on both sites had drillers records and camera survey evidence of fissures between 35 to 40mbgl in addition to potential deeper cavities.

Both wells were drilled following the EPA Advice Note 14 approach whereby the upper well chamber casing was drilled to 35mbgl at a wide diameter with some shallow mild steel casing to prevent the subsoil and upper weathered rock from collapsing into the hole. A Boode PVC well chamber casing was installed with tremie pipes connected. The grout was injected to the annulus and shown to eject the water from the annulus as injection continued. The injection was maintained until a consistent grout density emerged from the top of the casing.

The grout was allowed to set for 48hours and then drilling recommenced through the production section. Both boreholes encountered large karst cavities, and both had significant sediment filled fissures. Both wells were ceased at 80m due to the present of significant sediment filled fissures which overwhelmed the sediment management system on site.

The outflow from the Adare site during airlifting was estimated as 140m^3/hr, whereas the flow from the Croom site was 35m^3/hr. Both sites have required extensive well development to aim to reduce sediment ingress to the well. This has included airlifting with the rig, airlifting with a compressor and eductor type system, well vacuuming, surge pumping and gradually increasing the pumping rate over longer periods of time.

The Adare site is currently served by a river water abstraction, the treatment plant for which will require a major upgrade if it is to continue in use. If the G1 production well is commissioned, with a second production well as standby, this will offer a huge cost saving as the tertiary treatment plant will not be required for the abstraction. The current demand for the town is approximately 60m^3/hr but this can rise to 70m^3/hr in the summer due to tourism. The new G1 production well was pumped at rates of up to 75m^3/hr with minimal drawdown.

The Croom town supplies includes the pre-existing production well at the By-pass site, a smaller well on the opposite side of the By-pass and a spring supply at Skagh supplying 12m^3/hr. The supply is on the EPA's Remedial Action List (RAL) and the commissioning of a G1 supply will allow the site to be removed from the RAL and prevent significant expense associated with installing additional treatment at the sites.

CONCLUSIONS

There is now ample guidance and advice available for the development of high quality groundwater supplies in Ireland. Irish Water have adopted these designs as their G1 production well classification and proposed that wells constructed to the EPA Advice Note 14 only require chlorination. This offers major reduction in treatment costs when compared to supply requirements for surface water sites or less well protected groundwater supplies.

A paradigm shift is required for the sustainable development of groundwater supplies from a focus on a single borehole solution for each individual site to having multiple wells constructed to G1 status abstracting at lower rates to provide better quality water, with lower treatment requirements, lower pumping costs and more resilience to drought when it occurs. This will lead to a more mature and sustainable management of our groundwater resources and assets.

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SUPPLY-SIDE ACTIONS AT THE PORTLAOISE PUBLIC WATER SUPPLY WELLFIELD

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ABSTRACT

Absolute drought conditions prevailed from late June until mid-July 2018 in the East Midlands. In response, Irish Water established a Groundwater Source Protection Programme, and under this programme is currently seeking to supplement the existing Portlaoise Water Supply Scheme (WSS), specifically the Coolbanagher Wellfield[5]. This wellfield is currently supplied by a single production well, PW10. Approximately 1,000m^3 of groundwater is pumped daily from PW10 to Kilminchy Water Treatment Plant, prior to public distribution. Three additional boreholes (PW7, PW8 and PW9) were drilled and installed in 2009; however these were never commissioned. The proposed Coolbanagher Wellfield scheme involves commissioning these boreholes using a multidisciplinary approach. A hydrogeological appraisal was undertaken by Atkins to feed into the scheme design. Based on the appraisal findings, groundwater from wells PW7, PW8 and PW9 is deemed suitable for potable use. No significant well remedial works are warranted at any of the boreholes. All three boreholes, once fully commissioned, will be classified as G1 boreholes[6] and will provide an additional sustainable yield of c. 4,200m^3/d to the Coolbanagher Wellfield. This will ensure the Portlaoise WSS is protected against future impacts of seasonal and climate related pressures. A review of groundwater level monitoring data in the general East Midlands region suggests that compared to recovery periods during the preceding ten years, after the 2018 drought and relatively dry winter season, both the duration and the scale of aquifer recovery is reduced. This may potentially result in supply pressures during the coming summer, depending on future rainfall levels.

INTRODUCTION

2018 was a year of Irish weather extremes, from record low temperatures brought about by Storm Emma in spring, to a summer of heatwaves and drought. Drought conditions prevailed from early June until late July. The season's highest temperature of 32°C was recorded at Shannon Airport, Co. Clare on the 28th June 2018; this was the station's highest recorded temperature since 1946.

Absolute drought conditions were encountered from late June until mid-July at stations in the East Midlands (Met Éireann, 2019). An absolute drought is defined by Met Éireann (2018) as *'a period of 15 or more consecutive days to none of which is credited 0.2mm or more of precipitation (that is, a daily rainfall total < 0.2mm)'*. The effect on groundwater resources in the region was swift and highlighted the vulnerability of our public water resources to seasonal extremes. The resulting National Water Conservation Order ('hosepipe ban') implemented by Irish Water from the 6th July as a necessary emergency measure, resulted in impacts to agriculture and recreation. In response to this evolving situation, Irish Water established a Groundwater Source Protection Programme. Hydrogeological assessments of key public water supplies were commissioned on a regional basis using a risk based approach. Atkins is one of the consultants appointed to the East Midlands region under this programme, and is currently providing technical advice in relation to the

[5] This wellfield is a subset of the Kilminchy Water Treatment Plant (WTP). In total the Portlaoise WSS is currently made up of eight boreholes sources (at Eyne, Straboe, Coolbanagher, Derrygarran and Ballydavis), and produces c.7.5 megalitres a day (EPA, 2015) which is directed back to Kilminchy WTP. This new scheme will extend the Portlaoise WSS to a total of eleven borehole sources, which will produce a total of c.11.7 megalitres a day. This will result in a significant 36% increase in supply.

[6] As per Draft Irish Water Guidance (David Ball, 2017) '*Water Supply Borehole Classification G1-G5*'.

commissioning of three production wells in order to supplement the Portlaoise Water Supply Scheme (WSS).

SUPPLEMENTING THE EXISTING PORTLAOISE WATER SUPPLY SCHEME

Irish Water is seeking to supplement the existing Portlaoise WSS, specifically the Coolbanagher Wellfield, which comprises a total of four boreholes situated between Coolbanagher and Shaen, Co Laois (refer to Figure 1). These boreholes are installed within the underlying limestone bedrock aquifer, classified as '*Rkd'*, a regionally important karstified aquifer which is dominated by diffuse flow.

Figure 1. Regional OS map showing the location of the Coolbanagher Wellfield (Source: GSI, 2019).

The wellfield is currently supplied by one groundwater source, PW10. Groundwater from this production well (drilled and commissioned in 2009) is piped to Kilminchy Water Treatment Plant (WTP), where it is treated via chlorination and filtration, prior to public distribution. The current daily abstraction rate from PW10 is in the region of 1,000m^3. Three other boreholes (PW7, PW8 and PW9) were also drilled and installed in 2009 and are yet to be commissioned. Land-use in the vicinity of the Coolbanagher Wellfield is dominated by forestry and on a wider scale by agricultural land-use.

In order to effectively commission groundwater supplies from source to tap, a collaborative approach is required, drawing on the technical skills of a diverse range of professionals, from borehole specialists, hydrogeologists, civil, process, electrical and mechanical engineers, and various contractors to key stakeholders (including Irish Water, local authorities, the EPA, and NPWS). None of these roles are mutually exclusive. The long-term success of developing a 'fit for purpose' Water Supply Scheme depends on how these services are integrated during the delivery of a groundwater supply scheme.

The supplementary supply wells at the Coolbanagher Wellfield will be fully commissioned in accordance with CIRIA (Construction Industry Research and Information Association) 137 guidance *'Monitoring, maintenance and rehabilitation of water supply boreholes'* (CIRIA, 2003). This document provides best practice guidance on borehole monitoring, maintenance, rehabilitation and design and construction to optimise water supply from groundwater sources by encouraging a co-ordinated approach to borehole management.

THE PROPOSED COOLBANAGHER WELLFIELD SCHEME

The proposed Coolbanagher Wellfield scheme involves commissioning three boreholes (PW7, PW8 and PW9), which will be connected back to the existing pump house at the current public supply well, PW10, prior to being pumped to Kilminchy WTP for treatment and subsequent public distribution. The scheme will involve the following scope of works, which will be delivered using a multidisciplinary approach;

- Civils works - rising mains and pipe network to be installed along the existing forestry track, to connect the three boreholes (PW7, PW8 and PW9) to the existing pump house at PW10;
- Installation of new submersible variable-speed drive (VSD) pump at PW9, including c. 700m rising main and 2no.125mm power ducts;
- Installation of new submersible VSD pump at PW7, including c. 650m rising main and 2no.125mm power ducts;
- Installation of new submersible VSD pump at PW8 including c. 20m of rising main and 2no. 125mm power ducts;
- Mechanical / electrical works – installation of control gear and SCADA system;
- Civils works - rising main (consisting of 200mm, 250mm and 300mm internal diameter ductile iron), valves, electrical and communication ducting. Proposed cross connections at the Derrygarran source to (1) the Straboe raw water rising main (250mm internal diameter); and, (2) the Kilminchy WTP raw water rising main (450mm internal diameter);
- Well commissioning - to achieve desired flow rates and efficiencies;
- Handover and training of site representatives; and,
- Full site safety management including PSDP and PSCS for the installation.

CURRENT HYDROGEOLOGICAL SETTING - OVERVIEW

A preliminary hydrogeological appraisal was undertaken to feed into the scoping stage of the scheme. The following tasks were completed: desk-based review of all available information (including analytical data, and results for 2009 constant rate pumping tests run continuously for a period of between 14 and 28 days), hydrogeological borehole audit (at PW7, PW8 and PW9) carried out on 31st August 2018, and evaluation of the proposed scope of works for the scheme. The findings of the appraisal were used to develop the hydrogeological conceptual model for the Coolbanagher Wellfield scheme.

Overburden at the wellfield comprises 5m to 6m of peat, clay, sand and gravel, underlain by weathered limestone and dark grey/ black limestone (occasionally weathered reddish brown) of the Allenwood Formation (mainly pale grey, pure massive limestone, commonly dolomitised). Refer to Figure 2. Regional groundwater vulnerability rating for the Coolbanagher Wellfield is '*High'* (GSI, 2019).

The limestone bedrock aquifer is classified as '*Rkd'*, a regionally important karstified aquifer (diffuse). This type of aquifer is dominated by diffuse rather than conduit flow, with typically higher storage and many high yielding wells. Sustainable groundwater yields of 1,200m^3/d (PW7), 1,800m^3/d (for each individual supply - PW8 and PW9) and 1,440m^3/d (PW10) have been proven (Entec, 2011). Static groundwater levels measured on 31st August 2018 ranged from 3.145m below top of steel casing (mbtoc) to 6.105mbtoc. The Coolbanagher Wellfield has a reported transmissivity value of 300 m^2/d, hydraulic conductivity value of 3m/d and a hydraulic gradient of 0.010 (Entec, 2011).

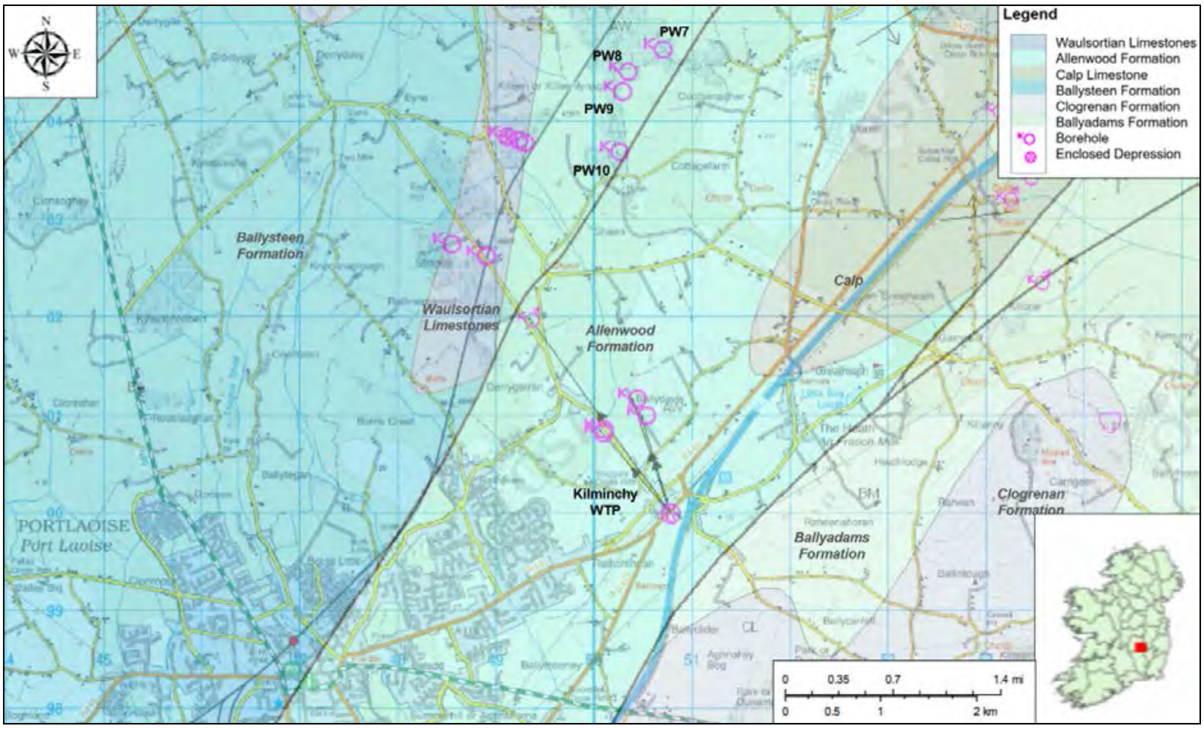

Figure 2. Regional map showing the locations of the Coolbanagher Wellfield (PW7 to PW10) and Kilminchy WTP, in the context of the underlying bedrock geology (Source: GSI, 2019).

Groundwater in the region forms part of the Bagenalstown Upper groundwater body (GWB) which is a major aquifer, comprising water-bearing units of pure limestone, dolomitised limestone and Calp. Dolomitisation is not complete; hence there may be areas of undolomitised limestone which act as aquitards (GSI, 2004). A low effective recharge value of 0.020m/yr[7] (peat underlain by regionally important karstified (diffuse) aquifer) applies to the wellfield area (GSI, 2019). However on a regional scale effective recharge values of up to 0.322m/yr have been estimated, and the presence of well-drained soils on higher ground and in other non-peaty areas, suggests that near-surface groundwater flow and surface runoff processes enhance the rate of recharge to the boreholes (Entec, 2011). Annual average rainfall at the nearby Emo Court Meteorological Station is 806mm (Entec, 2011).

The three wellfield boreholes (PW7, PW8 and PW9) were designed and installed in accordance with IGI (2007) and EPA (2013) best practice guidelines and can provide viable additional groundwater resources to the existing public water supply (of c. 1,000m^3/day from PW10). All three boreholes were drilled to final depths ranging from 101m (PW9) to 122m (PW7), with response zones as follows: PW7 (68-96m), PW8 (45-98.4m), PW9 (52-101m). All wells have a satisfactory cement grout seal.

The Source Protection Zone (SPZ) for the Coolbanagher Wellfield has been determined following several iterations; the current SPZ was modelled based on a detailed hydrogeological investigation completed in 2017 (Jacobs / TOBIN, 2017). The SPZ for PW10 is based on a refined conceptual site model (which takes account of both the limited degree of karstification in the vicinity of the wellfield, and the current pumping regime). The 100-day travel time (i.e. Source Inner Protection Area - SI) at PW10 is calculated to be 500m, as presented in Figure 3.

Raw groundwater quality within the Coolbanagher Wellfield is good, with no significant water quality issues identified at PW7, PW8 or PW9 (Entec, 2011). Based on a review of available analytical results for the monitoring period 2009-2017 no significant ongoing water quality issues are identified at PW10.

[7] Recharge co-efficient of 4% applied to effective rainfall value of 0.498m/yr.

Figure 3. Source Protection Zone for PW10 (Source: GSI, 2019).

In summary, the three boreholes (PW7, PW8 and PW9), which, once fully commissioned, will be classified as G1 boreholes, can supply an additional proven sustainable yield of c. 4,200m^3/d to the Portlaoise WSS (with minimal treatment). This will ensure the Portlaoise WSS is protected against the future impacts of seasonal and climate related pressures.

HYDROGEOLOGICAL CONCLUSIONS & RECOMMENDATIONS

Based on the appraisal findings, groundwater from wells PW7, PW8 and PW9 is deemed suitable for potable use (subject to appropriate treatment) and no significant well remedial works are warranted at any of the boreholes. The hydrogeological setting has been characterised as detailed previously. In order to commission the supplementary supply of up to c. 4,200m^3/d at the Coolbanagher Wellfield the following hydrogeological recommendations have been made:

- Submersible VSD pumps with maximum diameter of 150mm to be installed at PW7, PW8 and PW9, based on design criteria summarised in Table 1.
- Raw water sample tap to be installed at each well, along with SCADA system for ongoing monitoring purposes. Dip-tubes to be retained to facilitate manual groundwater level monitoring as required.
- All wells to be flushed.
- Step-test to be carried out under the supervision of a hydrogeologist at each well to verify yields, and to confirm that selected pumps are capable of the recommended range.
- CCTV survey of wells to be carried out if required.
- Raw groundwater samples to be collected and analysed for the full Drinking Water Suite (as per S.I. No. 122/2014 - European Union (Drinking Water) Regulations 2014, as amended). Analytical results to be screened and evaluated with recommendations provided as required.
- System to be disinfected during the commissioning stage.
- Secure compound to be constructed at each supply, similar to the design of PW10 (including secure fencing, warning signage, locked kiosk housing at each well head, locked pumping house and secure electrical substation).
- Source Protection Plan to be updated to include PW7, PW8 and PW9 (once commissioned).
- A maintenance programme, including water monitoring checks (in accordance with S.I. No. 122/2014 - European Union (Drinking Water) Regulations 2014, as amended, and Irish Water / EPA requirements) to be implemented for the supplementary supply.

- Monitored water levels and abstraction rates at each supply well to be regularly reviewed.

Well ID	Design Pump Depth	Technical Rationale	Design Pump Capacity Range	Technical Rationale	Design Abstraction Rate (subject to step test)	Technical Rationale
PW7	31.5m	Pump to be positioned above grouted casing as per EPA / IGI guidelines. Static water level: 6.680 mbtoc. Maximum drawdown during pumping test (at 1200m3/d): 34m. **Hence reduced pumping rate proposed.**	600 – 1,200 m3/d	Based on results of 2009 pumping test (steady rate of 1,200m3/d). Pumping range will provide options should future alterations be required.	600m3/d.	During the 2009 step test a drawdown of 11.04m was observed during Step 2 (100mins) at a pumping rate of c. 600 m3/d. Therefore, this is the proposed abstraction rate (taking account of the design pump depth (31.5m), and subject to step test during commissioning).
PW8	31.5m	Pump to be positioned above grouted casing as per EPA / IGI guidelines. Static water level: 2.985 mbtoc. Maximum drawdown during pumping test (at 1800m3/d): 6.7m.	900 – 1,800 m3/d	Based on results of 2009 pumping test (steady rate of 1,800m3/d). Pumping range will provide options should future alterations be required.	1800m3/d	Determined to be sustainable yield based on results of 2009 pumping test (including maximum drawdown) and taking account of proposed design pump depth (31.5m). Subject to step test during commissioning.
PW9	39m	Pump to be positioned above grouted casing as per EPA / IGI guidelines. Static water level: 4.176 mbtoc. Maximum drawdown during pumping test (at 1800m3/d): 5.5m.	900 – 1,800 m3/d	Based on results of 2009 pumping test (steady rate of 1,800m3/d). Pumping range required will provide options should future alterations be required.	1800m3/d	Determined to be sustainable yield based on results of 2009 pumping test (including maximum drawdown) and taking account of proposed design pump depth (39m). Subject to step test during commissioning.

Table 1. Recommended Pump Design Criteria for PW7, PW8 and PW9 (Source: Atkins, 2019).

DETAILED DESIGN AND PROCUREMENT

The preparation of tender documentation, along with the design of the proposed Coolbanagher Wellfield scheme have been completed by Nicholas O' Dwyer Limited. Detailed design will be undertaken by the Civil, Mechanical and Electrical, and Design and Build Contractor. Irish Water are currently at Tender Stage on this scheme.

LOOKING AHEAD TO SUMMER 2019 – A REVIEW OF GROUNDWATER LEVEL TRENDS AT SELECTED MONITORING LOCATIONS IN THE EAST MIDLANDS

A review of long-term groundwater level monitoring data in the East Midlands region has been undertaken. Two active EPA monitoring stations in Vickerstown, Co. Laois and Ballyragget, Co. Kilkenny[8] are installed within the same aquifer as the Portlaoise WSS; the Vickerstown station is also installed in the same GWB (Bagenalstown Upper GWB) as the Coolbanagher Wellfield. Monitoring locations are presented in Figure 4. Refer to hydrographs presented in Figure 5(a) and Figure 5(b). Available groundwater level data suggest that following the 2018 drought regional groundwater levels did not recover until late November 2018. This impact was observed at the Portlaoise WSS, as local households and businesses were urged to continue to conserve water due to sustained pressure on this resource during this time. Indeed persistent low rainfall levels had resulted in historic low water supply levels and Irish Water noted that the scheme did not have sufficient storage to sustain a full water supply in order to serve the population dependent on it (28,000 customers) over the winter season.

[8] Based on data obtained from the following active EPA monitoring stations (EPA, 2019); Vickerstown station ref - IE_SE_G_0153_1600_0014; Ballyragget Glanbia station ref - IE_SE_G_0163_1500_0002.

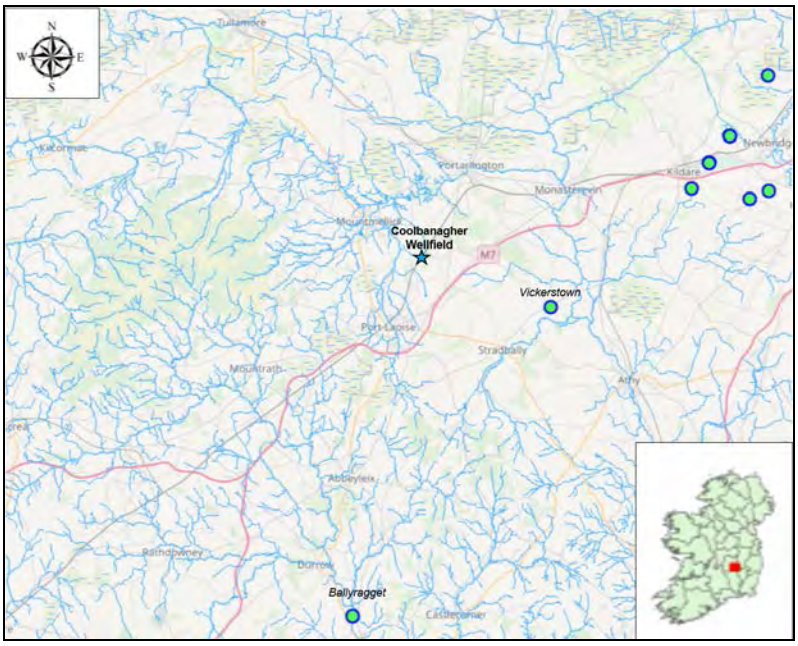

Figure 4. Active EPA Groundwater Level Monitoring Stations in the East Midlands Region (Source: EPA, 2019).

Slow groundwater level recovery during November is not unusual for the bedrock aquifer in this region (refer to Figure 5(a)), and is likely a function of the hydrogeological setting. However during 2018, the seasonal recovery period appears to have been particularly short-lived. The following hydrographs show groundwater levels within the regionally important karstified aquifer falling again from January 2019, a consequence of the mild and dry winter/ spring season we are currently experiencing. This is inconsistent with previous annual trends; groundwater levels generally show an increasing trend from December through to March, as storage within the aquifer is usually replenished via rainfall recharge.

Figure 5(a). Hydrograph showing continuous regional groundwater levels for the monitoring period 2014 to 2019 (Source: EPA, 2019).

Compared to recovery periods during the preceding ten years (refer to Figure 5(b)), it is clear that following the 2018 drought, both the duration and the scale of aquifer recovery are reduced in the region. This may potentially result in supply pressures during Summer 2019, depending on future rainfall levels. The 2018 drought highlighted the need for improved understanding of the aquifers which supply our groundwater derived public water sources. Routine monitoring and data evaluation will help characterise aquifer responses to groundwater pressures (including future extreme and unpredictable weather events associated with climate change impacts).

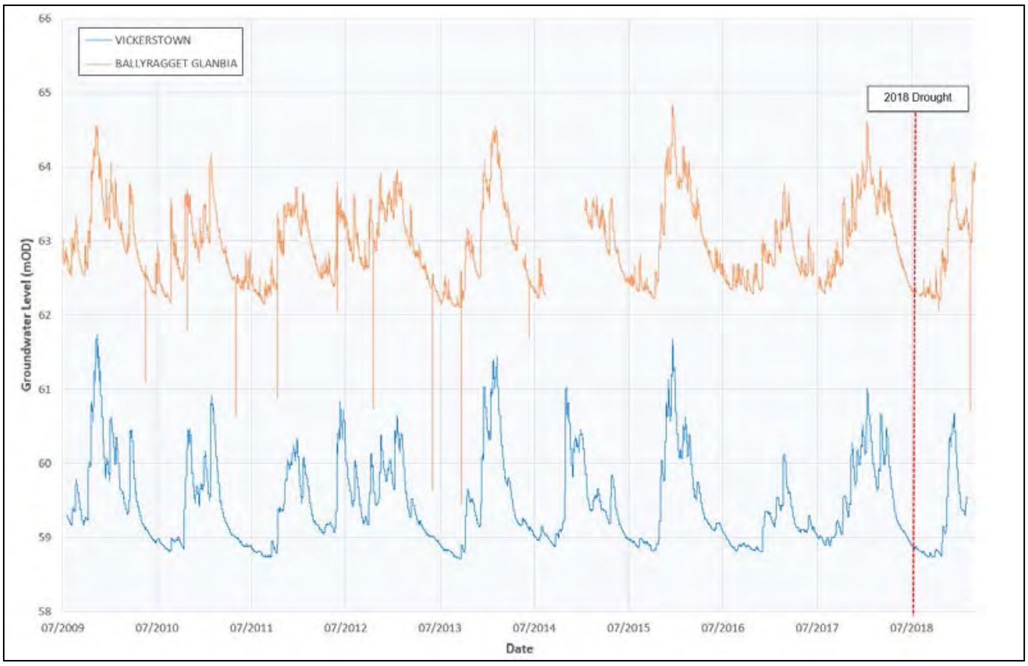

Figure 5(b). Hydrograph showing continuous regional groundwater levels for the monitoring period 2009 to 2019 (Source: EPA, 2019).

CCTV / CAMERA SURVEY

One of the skills which borehole specialists bring to the collaborative area of groundwater assessment is the CCTV or camera survey, which has become increasingly common in recent years. On a site such as the Coolbanagher Wellfield, where wells were historically drilled and tested but never commissioned, this field technique has proven particularly useful. The survey is usually undertaken in order to identify any structural issues within the well installation, to assess any potential clogging of the screen (via sediment build-up, biofouling, or, in supersaturated aquifers, precipitation of iron /manganese), or to verify installation and well screen details in the absence of detailed logs / borehole records.

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SESSION V

CLIMATE CHANGE - ARE WE GOING TO DO SOMETHING ABOUT IT?

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ABSTRACT

Floods and droughts are some of the biggest expected impacts arising from climate change. SEPA's new approach is to meet these challenges, and others like them, by making the environment a major business issue, not a side-line issue. In future, for successful businesses, the environment needs to be seen as an opportunity, not a problem.

SEPA's STRATEGY

According to the ecological footprint index[1], Scotland is using approximately three planets to sustain its current living. There is however, only one planet and most nations around the world face the dilemma of significantly over-using the planet's capacity to support human activity.

This represents one of the major challenges facing humanity and environment agencies must find innovative and more powerful ways of regulating, if they are to rise to this challenge and play their role in tackling it.

So, what are we going to do about it?

Terry A'Hearn, SEPA's Chief Executive, has challenged SEPA staff to imagine a point in a few years time, looking back with their children and explaining what they did to help stop climate change destroying their way of life. In a recent interview he stated[2] that "*If you bring everyone up to compliance you might go from using up three planets to 2.7 planets. You've still got huge environmental damage and huge threats to the economy and society so we have to get everyone to compliance and then go further.*" So, SEPA's strategy[3] is called "One Planet Prosperity" and focuses on taking industry sectors beyond compliance.

This means making the environment a major business issue, not a side-line issue. In future, for successful businesses, the environment will be an opportunity, not a problem.

This work is already underway, via a huge switch in SEPA's focus to delivering plans for each of the sectors we regulate. The sector plans are developed via engagement with the sectors, internal experts, relevant regulators and other key stakeholders. Sector plans focus on practical ways of delivering environmental, social and economic outcomes. They specify existing levels of compliance, the market context for that sector and the key issues faced by the sector and SEPA. This includes social issues

[1] www.footprintnetwork.org/en/index.php/GFN/

[2] https://www.endsreport.com/article/1527766/agent-change-interview-sepa-chief-executive-terry-ahearn

[3] https://www.sepa.org.uk/media/219427/one-planet-prosperity-our-regulatory-strategy.pdf

such as recognising the importance of creating local jobs in rural communities and any issues that non-compliance is creating in the communities the sector is operating in. Taking this planned approach ensures we are systemically tackling the remaining compliance issues for the sector, mapping out where the most promising ‘beyond compliance’ opportunities exist and identifying and harnessing the key levers that influence that particular sector. Examples of levers include supply chain requirements, consumer demand and industry standards.

At the time of writing, SEPA has 15 sector plans either underway or under consultation[4]. These include landfills, whiskey, crop production, housing and water/wastewater. Forestry will soon be out for consultation and a further batch of sectors are planned next year.

At the heart of One Planet Prosperity is the explicit statement that “compliance is non-negotiable”. The mechanisms under the strategy make it easier for SEPA to ensure we can get full compliance with environmental regulations from all the sectors we regulate. SEPA will have zero tolerance for those who do not want to meet Scotland’s environmental laws, but will use a broader range of tools, everything from supply-chain influence to tough enforcement, to achieve this.

CLIMATE CHANGE PREDICTIONS

In January 2019, the UK Meteorological Office published “UKCP18”, a revised assessment[5] of climate change predictions for the UK through to 2100. They identified that annual average rainfall has already increased by just over 10% in the last decade compared to 1961-1990. Over the next century, they predict that temperatures will rise such that the chances of a summer like 2018 will increase from less than 1 in 10 (1990) to roughly 1 in 2 (2050). Associated with this rise in temperature:

- Winter rainfall in Glasgow is expected to increase by ~25% by 2100.
- Summer rainfall in Glasgow is expected to decrease by ~30% by 2100.
- Extreme downpours will be heavier. Hourly rainfall is expected to increase by 40% on average.[6]
- Mean sea levels near Edinburgh are expected to rise by up to 0.9m by 2100, even in Scotland where the land is also rising.

So, it’s clear we need to be adapt to increased floods and droughts.

DROUGHTS

In a speech, at the Waterwise Conference (March 2019), the CEO of England’s Environment Agency coined the term “jaws of death” [7]. He used this term to describe a point in 2050 when water demand in England potentially outstrips supply. He also quoted Sylvia Earle, the distinguished marine biologist, as follows: “*No water, no life. No blue, no green. No ocean, no us.”* Clearly he is taking drought risk seriously.

The UKCP18 work indicates we also need to plan ahead in Scotland. Though we will still have more summer rain than most parts of Europe, the percentage change is potentially dramatic and this could hit us hard if we are not prepared.

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[4] https://sectors.sepa.org.uk/

[5] https://www.metoffice.gov.uk/research/collaboration/ukcp

[6] Chan, S., Kahana, R., Kendon, E., Fowler, H. 2018. “*Projected changes in extreme precipitation over Scotland and Northern England using a high-resolution regional climate model*”. Climate Dynamics. November 2018, Volume 51, Issue 9–10, pp 3559–3577

[7] https://www.gov.uk/government/speeches/escaping-the-jaws-of-death-ensuring-enough-water-in-2050

SEPA has a locus in drought adaptation via the regulation of abstractions and impoundments. The summer of 2018 brought record harvest to fruit farmers in Scotland but brought economic impacts to a number of other sectors, including hydropower, distilling and potato and livestock farming. Hydropower lost 25% of expected generating capacity. Some distilleries had to cease production were rivers were too warm to be used for cooling. The public water supply was largely unaffected, but the supply for the Isle of Arran had to be supplemented by tankering water across the Firth of Clyde. Private water supplies were much harder hit. Several hundred private supplies in North East Scotland went dry, also incurring significant costs for tankering water. In fact, some private supplies were still receiving tankered water in February 2019.

To help Scotland adapt, SEPA is working with the sectors affected to make better storage and more efficient use of water an economic opportunity.

Crop production is a good example. We know that security of supply for irrigating farmers, especially in drought situations, is essential. This guarantees a good crop and provides certainty to the industry, to supermarkets and to the consumers. Certainty provides economic benefit because those farmers that can provide it are more likely to get profitable contracts. SEPA's Crop Sector plan highlights how crop growers can become more resilient to droughts as healthy soils store more water and the crops require less irrigation and fertiliser. This is a clear win-win, resulting in both prosperous businesses and less risk of environmental damage or pollution. The Crop Sector Plan also highlights that farmers can build resilience, either alone or as a collective within a catchment, by optimising the timing of abstractions from surface, groundwater or storage ponds. SEPA is also providing the following direct incentives to farmers making better provision for storage of irrigation water:

- For those switching river abstractions to groundwater, applications are determined faster and have a reduced charge of 30% of the normal fee.
- For those abstractions to ponds or off-line impoundments that are filled during winter and store at least 75% of the water required during the summer, there is a charging discount of 62%.

As a next step we will soon be consulting on amendments to the way abstractions are regulated at times of low flow to make it clearer for industry to understand and therefore achieve compliance requirements. SEPA is also working to provide as much warning and information as possible to allow industry to prepare for droughts[8]. We have in fact been flagging the risk of water scarcity for summer 2019 since January 2019.

FLOODS

Flooding is one of SEPA's two main corporate priorities:

- SEPA helps Scotland avoid the risk of flooding to new communities and new economic development via planning advice to Local Authorities.
- Where existing communities and businesses can't avoid the risk of flooding, SEPA helps them adapt. We work collaboratively with Local Authorities, Scottish Water and other partners to help them develop and implement flood risk management plans.
- As a last line of defence, SEPA is Scotland's flood warning authority. Where it is not possible to completely avoid or eliminate the risk of flooding then we give communities and emergency responders 24/7 advance notice of flooding. We also help them to be prepared and protect themselves in advance.

[8] https://www.sepa.org.uk/environment/water/water-scarcity/

We now estimate that 284,000 homes, businesses and services are at flood risk in Scotland[9]. Surface water (intense rainfall, drains, etc) is by far the biggest source of flood risk to homes in Scotland. Climate change presents Scotland with a major flooding challenge. We estimate that it will increase the numbers at risk by an estimated 110,000 properties by 2080. The risk from all sources is likely to increase as a result of climate change, but there are particular concerns for increased risks from surface water and coastal flooding.

Some of Scotland's most valuable land occurs on the coast, along rivers and in towns. These are places where people want to live. How do we facilitate economic development whilst also ensuring that people and property are not put at increased risk? How do we help communities already at risk adapt? How do we engage with communities and businesses in a way that makes the most difference? To meet this challenge, SEPA will soon be consulting on a new flooding strategy.

Certain sector plans such as housing, infrastructure and water all feature significantly in the flooding strategy. That's because the strategy will follow "One Planet Prosperity", aiming to help Scotland be one of the first places in the world to successfully tackle our changing climate while benefiting from economic prosperity that is more lasting, inclusive and resilient. One example that we will explore in this process is to seek closer collaboration with the insurance and finance industries. This is with a view to better sharing of information and potentially even establishing a mechanism that places liability for future flood damage with the site developer. Another example is helping the construction industry plan ahead to avoid costly delays in the planning process by providing better and clearer flood risk information and guidance up-front. Perhaps most importantly, we will be exploring how best to make flood avoidance a fundamental part of the design of sustainable place-making in future.

SUMMARY

SEPA's approach to dealing with climate change is to make environmental success an economic opportunity, not a problem. We are working to bring environmental issues to the attention of boardrooms as well as plant managers. We are working to collaborate closely with partners across the public and private sector to bring all the levers and influences to bear that we possibly can. Will our children expect anything less?

[9] https://www.sepa.org.uk/environment/water/flooding/developing-our-knowledge/

GROUNDWATER FLOODING IN IRELAND: NEW METHODS FOR FLOOD MONITORING AND MAPPING

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ABSTRACT

Unprecedented flooding in winter 2015/2016 across the karst limestone lowlands in the Republic of Ireland reinforced the need for a greater understanding of groundwater flooding as a geohazard and improve our ability to quantify the location and likelihood of flood occurrence. The nature of groundwater flooding on the lowland karst limestone regions poses significant technical challenges. These lowland karst limestone regions are susceptible to groundwater flooding due to the combination of low soil and aquifer storage, high diffusivity and limited surface drainage. The lack of appropriate monitoring infrastructure was subsequently highlighted as a major impediment to effective groundwater flood risk management. In response, Geological Survey Ireland commenced the establishment of a telemetric groundwater flood monitoring network across the region. An exploratory monitoring network of over sixty sites was established over an 18 month period to improve the understanding of groundwater flooding regimes and provide baseline data for the telemetered site selection process. Selected sites have been instrumented with telemetric systems allowing real-time monitoring of groundwater flood data. Multi-temporal Synthetic Aperture Radar (SAR) imagery was used to delineate flood extents and water elevation during the extreme flood events in 2015/2016 at gauged and ungauged sites. Maximum flood extents derived from SAR imagery from this event were combined with limited field observations to produce historic and predictive groundwater flood maps for Ireland as part of the 2nd implementation cycle of the EU Floods Directive. Furthermore, series of SAR images have been combined with high resolution topography to construct hydrographs to improve the fundamental hydrogeological understanding of groundwater flooding enabling key stakeholders to develop appropriate flood mitigation measures and for informed flood assessments to be made in the future.

1. INTRODUCTION

The winter of 2015/2016 saw unprecedented rainfall levels across the Republic of Ireland. A succession of storm fronts crossed Ireland between November and February that resulted in persistent rainfall. Over 600mm of rain fell between the winter months of December and February, representing 190% of the average making it the wettest winter on record stretching back to 1850 (McCarthy et al., 2016; Noone et al., 2016). This continuous rainfall resulted in rivers bursting their banks, caused widespread flooding and resulted in the most extensive groundwater flooding on the karstic limestone in the west of Ireland (Naughton et al., 2017) (Figure 1). This flooding caused impacts on communities, damage to properties, and disruption to road access and impacted heavily on agricultural land with affected areas lasting for months.

There are two primary factors associated with groundwater flooding; prolonged high levels of rainfall and drainage governed largely by subsurface flow paths. Groundwater flooding in Ireland is associated with limestone areas of the western lowlands of Clare, Galway, Mayo and Roscommon extending from the River Fergus in Co. Clare upwards to east of Lough Mask and Lough Corrib Co. Galway and southern Co. Mayo. These areas are susceptible to groundwater flooding due to the combination of high rainfall on aquifers characterised by high spatial heterogeneity, low storage, high diffusivity, extensive interactions with surface and limited surface drainage. The vast majority of extensive recurring groundwater flooding occurs at low lying depressions known as turloughs. There are over 400 recorded turloughs located in limestone lowlands.

In response to the serious flooding of winter 2015 specifically related to turloughs, the Programme for a Partnership Government (2016), under the area of Climate Change and Flooding, contains the following objective: *"Turlough Systems: We will provide resources to the OPW to commission studies into individual problematic (prone to flooding) Turlough systems, if requested by a local authority or another relevant State agency"*. The phenomenon of groundwater flooding can pose significant risk to rural communities. In recent years the increased frequency of flood hazards highlights the clear need for further research into its increased frequency and risk assessment associated with groundwater flooding in karst regions. Geological Survey of Ireland (GSI), a division of the Department of Communications, Climate Action and Environment (DCCAE), were in a position to help deliver on this commitment through the existing groundwater and karst expertise and by the development of a three-year project on groundwater flooding.

GSI in collaboration with Trinity College Dublin and Institute of Technology Carlow has developed a monitoring, mapping and modelling programme, GWFlood. This programme provides the necessary data to address the groundwater hydrometric data gap by establishing a permanent telemetric network, analysing SAR images, and constraining the results with high resolution topographic mapping. Modelling tools have been developed to help address the issues with groundwater floods mapping and flood frequency estimations. A key output for this project is to produce historic and predictive groundwater flood maps for Ireland in line with the 2nd implementation cycle of the EU Floods Directive (Directive 2007/60/EC).

The EU Floods Directive requires all state bodies to reduce and manage flooding through mapping probabilistic flood extents. Mott MacDonald (2010) mapped the Preliminary Flood Risk Assessment (PFRA) phase primarily using an 'evidence-based' approach. However after the extensive flooding in the winter of 2015/2016 there was a need to re-examine and update historic groundwater flood maps. The GWFlood project has developed a groundwater flood mapping methodology for gauged and ungauged sites. Two types of flood maps are being developed. The first are Historic Flood Maps based on the 2015/2016 flood event combined with the observed flood information gathered in the PFRA. The second are Predictive Flood Maps which are being developed for areas where recurrent flooding (turloughs) occurs with Annual Exceedance Probability (AEP) predictions.

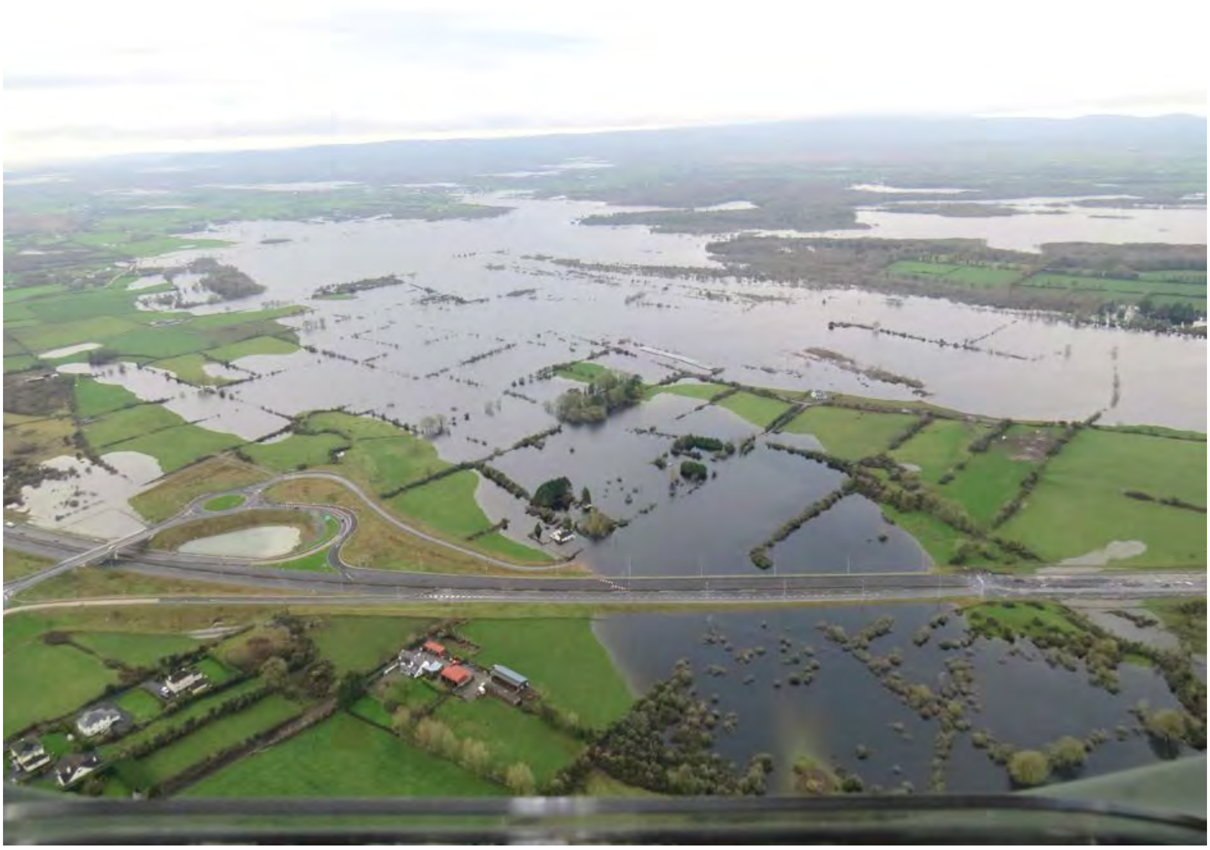


Figure 1: Groundwater flooding in South Galway, 2016 (photo courtesy of OPW).

2. FLOOD MONITORING

Turloughs have a general seasonal flooding pattern, they can however show a high level of fluctuation from year to year due to seasonal variability within the Irish climate (Waldren, 2015). It is when turloughs flood outside their ‘norm’ that can cause impacts. Historically there has been no systematic collection of groundwater flooding hydrometric data. Therefore two approaches were considered to address this knowledge gap: 1) exploratory monitoring network at specific sites to provide baseline hydrometric data, and 2) remote sensing procedure to delineate floods at gauged and ungauged sites during extreme flood events.

2.1 FIELD MONITORING

Rivers, lakes and oceans are monitored across the country providing hydrometric information for local authorities and planning agencies for flood risk management. Consistent long-term hydrometric data does not exist for groundwater. A primary objective of the GWFlood project is to provide baseline data for groundwater flooding by establishing a monitoring network system. Sixty exploratory monitoring sites were installed in November 2016 in turloughs and lakes across counties Roscommon, Mayo, Galway, Clare, Longford and Westmeath (Figure 2) measuring stage and temperature using Solinst Leveloggers®. Data from these sites helped to develop a preliminary understanding of the hydrodynamics and flooding potential of turloughs. Hydrographs represent the range of flooding regimes observed across the monitored turloughs (Figure 3). The hydrological regime varies across turloughs showing multimodal or unimodal flooding (Waldren, 2015). Turloughs follow a seasonal pattern in their hydrological regime yet individually their behaviour is unique even for turloughs that are hydraulically linked such as those in the Gort Lowlands, Co. Galway. The data collected from the exploratory monitoring network systems was used to inform the site selection process for the permanent telemetered monitoring stations. This approach is a new method for systematically recording groundwater flooding in Ireland. A subset of 20 sites is being established to provide real-time information on groundwater flood conditions. This installation began in summer 2017 and is scheduled for completion in mid-2019. Permanent real-time monitoring is a way of systematically monitoring turloughs and providing information on turlough flooding to authorities and the public. Data from these turloughs are monitored hourly using Van Essen TD-Divers. The data are transmitted through an optical reader to an Eijkelkamp GDT-S Prime modem via a transmission cable. The modem transmits data recurrently via SMS to an online web portal. The data from these turloughs will be publically available via an online web platform in the near future.

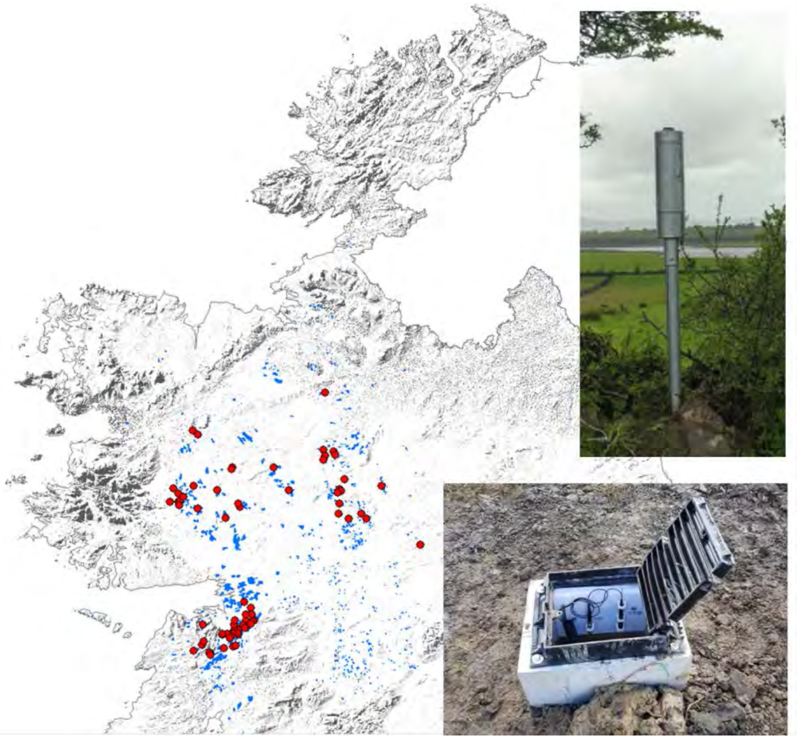


Figure 2: GWFlood exploratory Turlough Monitoring Network (red) overlaid on groundwater flood hazard sites (blue) (Mott MacDonald, 2010). Insets: Telemetric monitoring equipment.

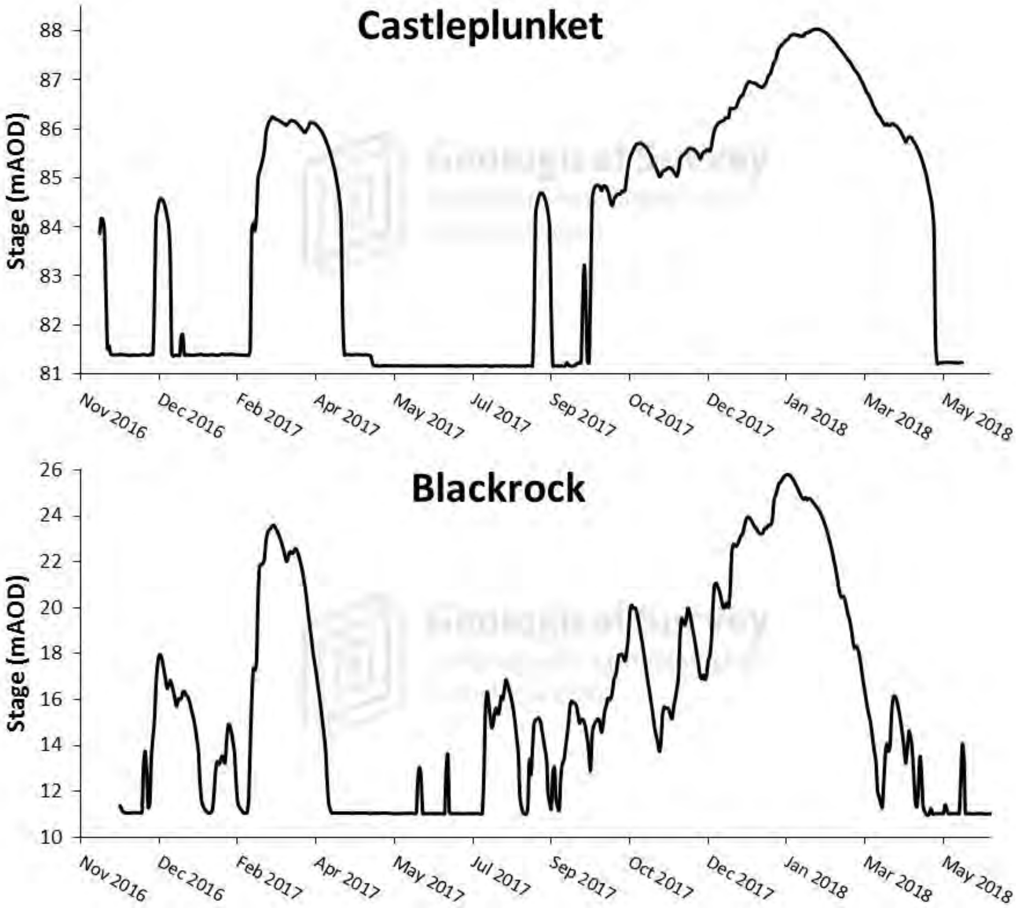


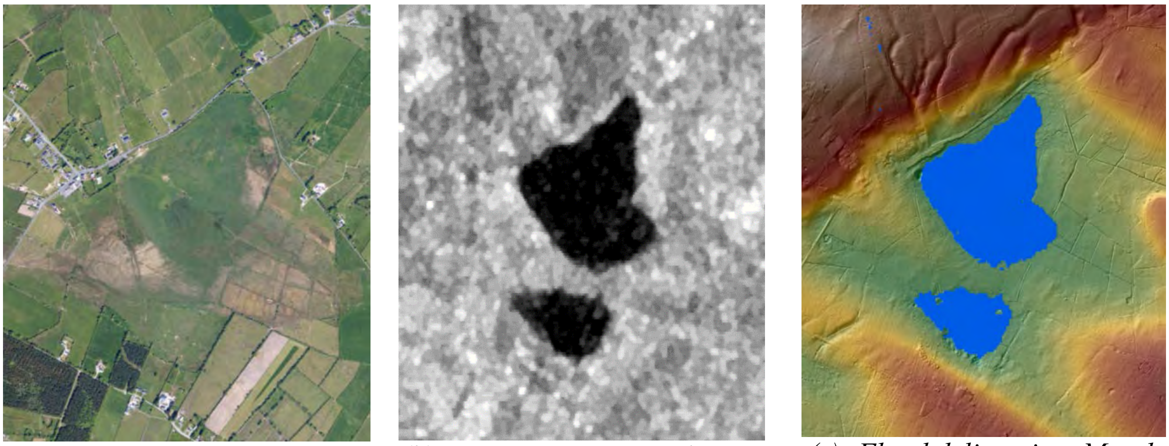
Figure 3: Hydrographs of Castleplunket in Co. Roscommon and Blackrock in Co. Galway.

2.2 REMOTE SENSING MONITORING

Monitoring groundwater using traditional field methods is an effective tool for gathering hydrometric data; however the distributed nature of groundwater flooding in karst lowland regions makes monitoring turloughs using field instruments impractical due to their large number and distribution. Earth observation along with a Geographical Information System (GIS) approache offers the ability to map large quantities of groundwater flooding across a large area being able to detect and quantify flood events at particular sites (Figure 4).

Earth observation technologies include optical multispectral and synthetic aperture radar (SAR) which can be used for remote sensing. USGS Landsat and European Space Agency (ESA) Sentinel-1 have been used to map groundwater flooding at a catchment scale. Landsat contains a multispectral imager providing high resolution images of the earth. It provides a long historical archive of images dating back to the 1980’s which allows for observation of historic flood events; however cloud cover is an issue and restricts clear view of the earth’s surface and data acquisition becomes limited.

ESA Sentinel-1 uses the SAR instrument, which can be used to map groundwater flooding remotely. The satellite emits radar pulses and records the return signal at the satellite. The strength of this signal, or backscatter, is largely dependent on surface roughness and geometry. Flat surfaces such as water operate as specular reflectors resulting in minimal backscatter signal returning to the satellite (Figure 4b). A big advantage with SAR is that it orbits the Earth at any time of the day or night and is independent of cloud coverage. These satellites have repeating paths which allows users to compare datasets for the same location at different times.



(a): Orthophotography *(b): SAR imagery, March 2017* *(c): Flood delineation, March 2017*

Figure 4: Imagery of Castleplunket turlough Co. Roscommon showing (a) orthophotography of it empty, (b) pre-processed SAR flood image and (c) flood delineation overlaid on LiDAR data.

For this project the Sentinel-1 satellite from the ESA was used for monitoring groundwater flooding. A benefit of Sentinel-1 is the 1 to 3 day revisit over Ireland collecting images since late 2014. Satellite images are more suited for groundwater flood monitoring which occurs at a much slower rate (weeks to months) than flash floods which can dissipate within hours and therefore more likely to be missed by the satellites. The 2015/2016 flood event was captured by Sentinel-1 due to its prolonged period, which allowed groundwater flooding to be tracked through time. By cross referencing the flood boundary of the turlough against high resolution topographic data the elevation of the water surface was calculated on the assumption that the water surface has a uniform elevation value. This process was repeated for every satellite orbit enabling the generation of dynamic flood mapping and hydrographs (Figure 5).

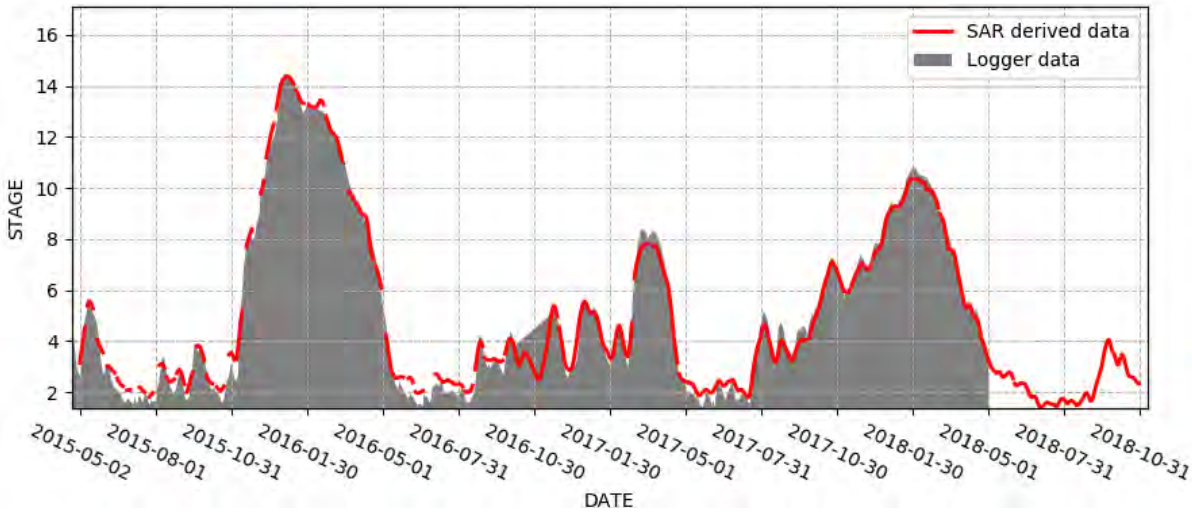


Figure 5: Sentienl-1 derived hydrograph (red) and observed logger data (grey) for Caherglassaun Turlough Co. Galway.

3. HYDROLOGICAL MODELLING

Predictive flood mapping requires long-term hydrological time series to estimate future occurrence probabilities. No such records exist for karst groundwater flow systems in Ireland; however, long-term records of rainfall are available. The GWFlood project developed a hydrological modelling methodology to quantity the relationship between rainfall and turlough flooding to reconstruct the requisite long-term hydrological series from observed and stochastic rainfall data.

There are two fundamental approaches to the mathematical modelling of karst hydrogeological systems; distributive models and global models (Kovacs and Sauter, 2007). Given the limited data availability in Irish karst groundwater flow systems, and the required broad application of the methodology, a global modelling approach was deemed the most appropriate. Global (or lumped parameter) models concentrate on mathematically deriving a relationship between input and output; they consider the karst aquifer as a transfer function, transforming the rainfall input signal into the output hydrograph signal. The transfer function is taken to represent the overall (or global) hydrogeological response of the karst aquifer to recharge events (Kovacs and Sauter, 2007). Here, two global models were developed which estimated turlough flood volume based on cumulative effective rainfall and the Antecedent Precipitation Index (API) respectively.

In both models, a simple Soil Moisture Deficit (SMD) model was used to estimate effective rainfall. The soil and unsaturated zone were represented as a single reservoir with the flux in the reservoir dependent on the inputs and outputs, namely rainfall (R) as the input and actual evapotranspiration (ET_A) and effective rainfall or recharge (R_E) as the output. The model structure and parameters were based on the SMD model developed for Irish grasslands by Schulte et al. (2005).

Cumulative effective rainfall time series were then constructed for each site by summing records over time windows ranging from 5 to 280 days. The cumulative rainfall model was in the form of a linear regression between cumulative effective rainfall (predictor) and wetland volume (response):

$$V = S + A * \sum_{t=-D}^{-(W+D)} R_E$$

where, S is the intercept, A is the slope, R_E is effective rainfall, while D and W are the time delay and window size corresponding to the highest cross-correlation value respectively.

The API, first proposed by Kohler and Linsley (1951), represents a continuous function of rainfall capable of increasing rapidly following rainfall followed by a gradual decay during dry periods. It assumes the effect of antecedent precipitation can be represented by catchment or site-specific recession coefficient (Beschta, 1998). Here a modified version of the API, the Current Precipitation Index (CPI) (Smakhtin and Masse, 2000), has been used to model turlough flood volumes and is given by:

$$CPI = \sum_{t=-1}^{-i} P_t k^{-t}$$

Where i is the number of antecedent days, k is a decay constant and P_t is rainfall on day t. The CPI series using a range of k values were generated, with the k value showing the best linear regression fit to turlough flood volume selected. Models using both the cumulative rainfall and the CPI approach are fitted to each site, with the best fit model selected based on the Nash-Sutcliffe and Kling-Gupta model efficiency criteria.

4. FLOOD MAPPING

Remote sensing provides an effective means of mapping location, extent and changes of surface water over time. Monitoring water bodies using SAR remote sensing has been demonstrated as a suitable tool for floodwater mapping by numerous studies (Bolanos et al., 2016; Chini et al., 2019; Klemas et al., 2015). The GWFlood project has developed in-house image processing techniques to detect groundwater flooding extents from SAR data. Combining satellite derived flood extents with high resolution topographic mapping makes it possible to extract water level information from each satellite image. In this method water is separated from land through the ability to differentiate water and land pixels. The flood mapping methodology consists of five broad stages (Figure 6).

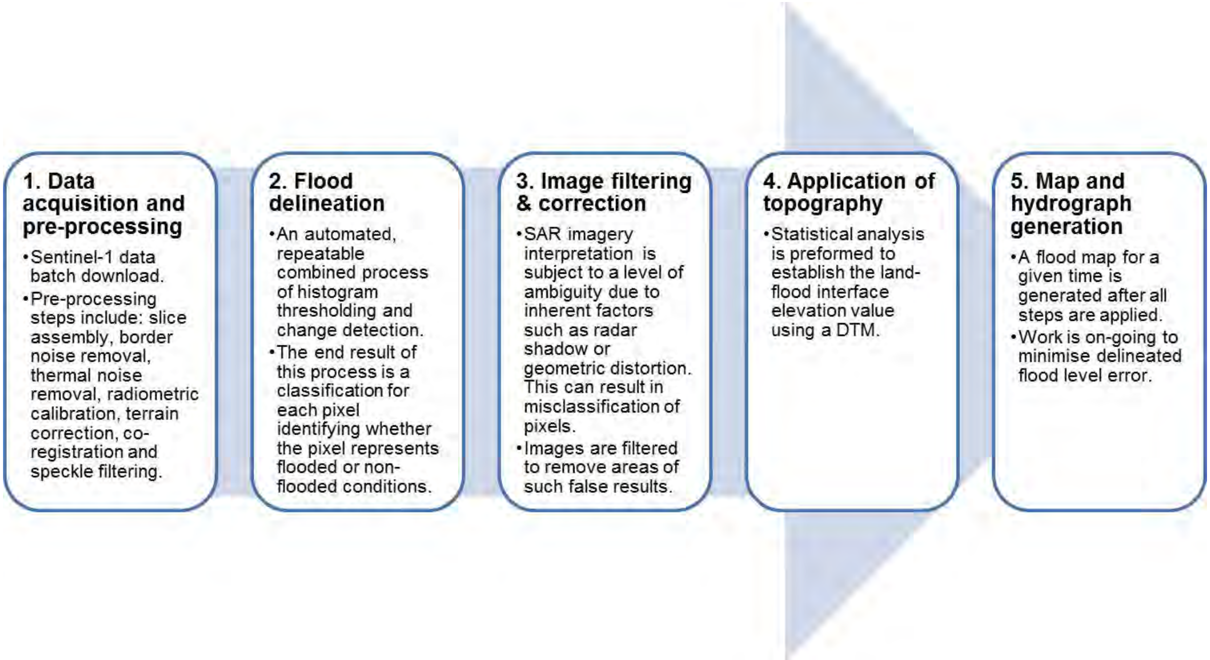


Figure 6: Remote sensing flood mapping methodology stages.

The GSI has generated two different types of flood maps as part of the GWFlood project: 1) historic flood map, and 2) predictive flood map.

4.1 HISTORIC FLOOD MAP

The historic groundwater flood map shows the extent of observed historic groundwater flood extents in karst areas. This map was largely based on the combination of the 2015/2016 event using the systematic acquisition of Sentinel-1 SAR images, observed flood data gathered during the GWFlood project and the first PFRA. In order to assess accuracy using remote sensing technologies to accurately delineate water bodies, SAR data was compared with observed logger data recorded by GSI for the same dates. During the process of mapping historical flooding when recurrent flooding is detected and the turlough basin meets the criteria for topographic correction an additional water delineation stage is applied. This process estimates a peak flood elevation for each SAR image rather than the classifying each pixel water and non-water. Then using the SAR generated hydrographs a maximum flood contour is derived from a digital terrain model using the highest observed flood level, thus imaging the flood extent also in regions where SAR imagery is subject to a level of ambiguity and cannot constrain the presence of water. A good example of this is radar shadows on leeward hillsides or geometric distortion caused by forestry. The national historic groundwater flood map is due for completion at the end of Q1 2019 (see Figure 7 for an initial draft map). An expanded ‘all flood types’ map will then be developed using the same techniques and will be produced mid-summer 2019.

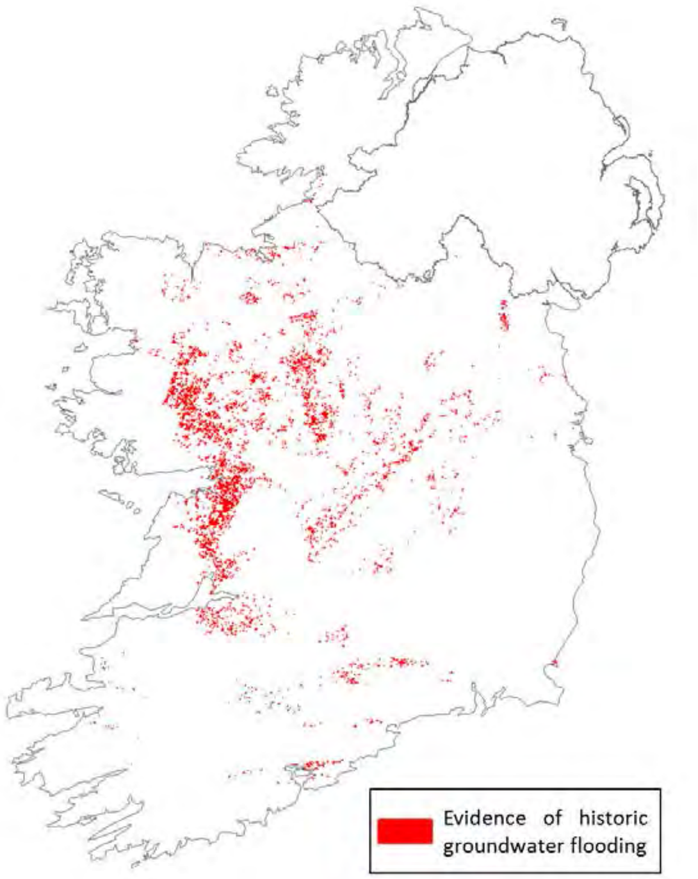


Figure 7: Draft of national historic groundwater flood map.

4.2 PREDICTIVE FLOOD MAP

Predictive flood map shows the probability of an area to be affected during flooding events. A conceptual approach to predictive groundwater flood mapping is shown in Figure 8. The generation of predictive groundwater flood maps for specific sites consists of combining the observed SAR-derived hydrograph data, hydrological modelling, stochastic weather generation and extreme value analysis.

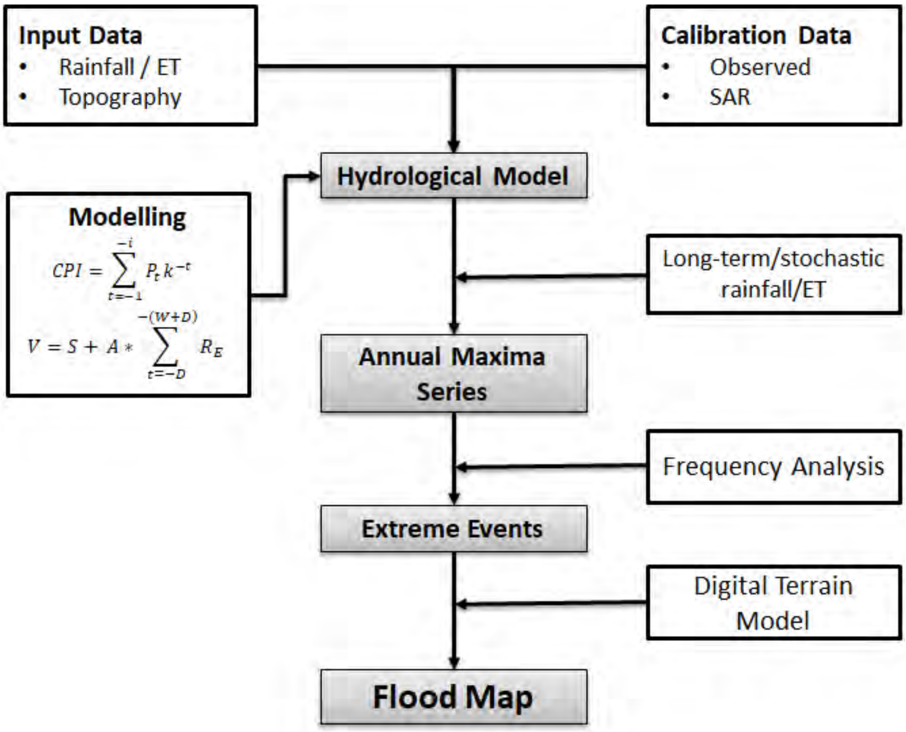


Figure 8: Flow chart for predictive groundwater flood mapping methodology.

The predictive groundwater flood map is site-specific and dependent on several factors including: 1) the quality of the SAR images, 2) the size of the turlough, and 3) the topography characteristics. For suitable sites a hydrological model capable of reproducing groundwater flooding time series was calibrated from antecedent rainfall and soil moisture conditions. Met Éireann meteorological data was then used to calibrate a stochastic weather generator algorithm from Chen et al., (2010) to generate long-term (1000+years) synthetic rainfall data for each site. This stochastic time series and average evapotranspiration (ET) were used as input data to produce long-term volume time series for each site.

A statistical distribution was fitted to the annual maxima, from which predictive groundwater flood extents were extracted and used to generate predictive maps. The type of statistical distribution chosen varies across the turloughs depending on the best fit. Figure 9 shows the resulting Annual Exceedance Probability (AEP) map at Castleplunket turlough, Co. RAEP

In addition to predicative mapping for current climate conditions, the modelling procedure can be adapted for climate change scenarios. Recent climate change studies of Ireland (Nolan, 2015) indicate that winter rainfall is likely to increase while summer rainfall will likely reduce over the coming decades. Additionally, the frequency of heavy rainfall events is likely to increase by 20% during autumn and winter months. Preliminary modelling indicates that these changes of the hydrological cycle will likely result in an amplification of groundwater flooding behaviour. Turloughs will likely be drier for longer in the summer with increased flooding in the winter (in terms of both stage and duration). The drier summers are unlikely to compensate for wetter winters as seen in 2015 dry summer leading into the 2015/2016 winter floods possibly due to the limited storage in the karst system.

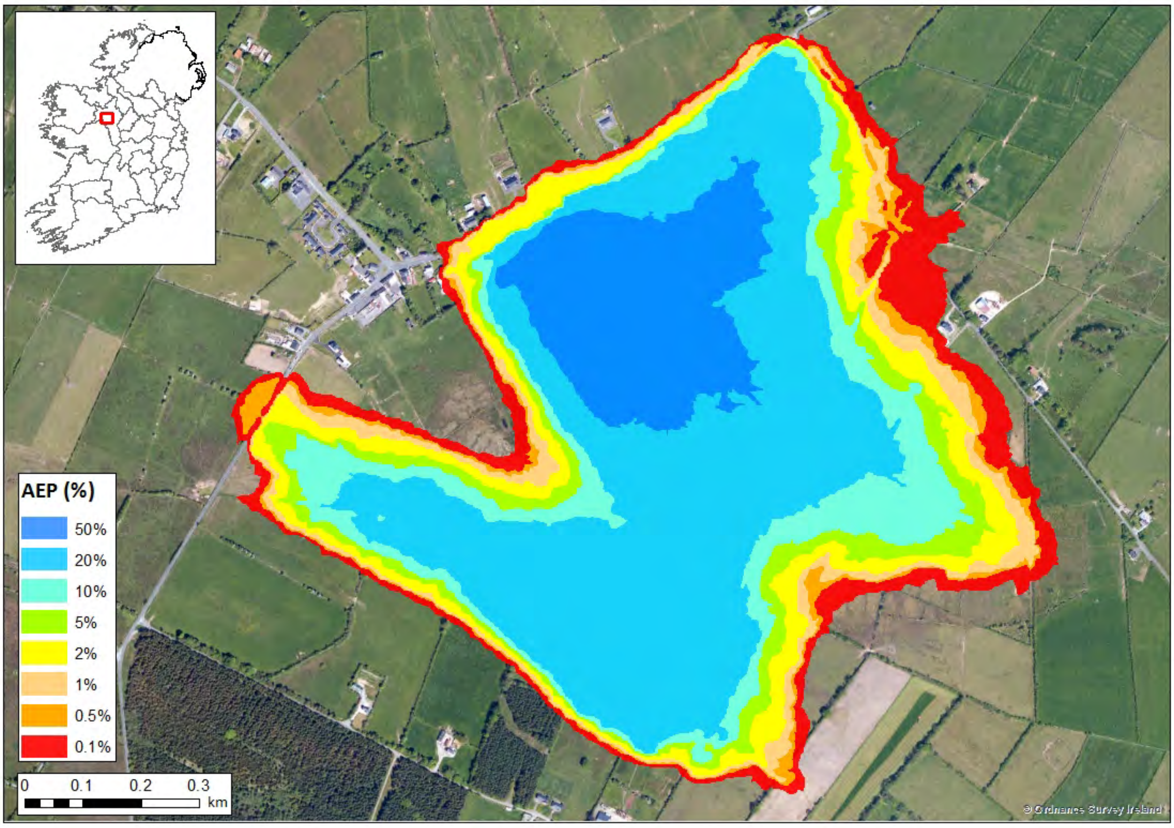


Figure 9: Annual Exceedance Probability (AEP) flood extents at Castleplunket turlough Co. Roscommon.

5. CONCLUSIONS

Traditional field measurements, SAR images, and high resolution topographic data were successfully combined to map and monitor groundwater flooding. This study presents preliminary results towards: 1) a new systematic permanent telemetric monitoring network, 2) the Historic Flood Map, and 3) the Predictive Flood Map for the Republic of Ireland. The presented results already provide a greater understanding of the impact of groundwater flooding as a geohazard, and improve our ability to quantify the location and likelihood of groundwater related? flood occurrences. The final maps will be presented at the end of 2019 as part of the 2nd implementation cycle of the EU Floods Directive. These maps will provide robust and valuable information for mitigating the geohazard that groundwater flooding poses to Irish society.

ACKNOWLEDGMENTS

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SESSION VI

THE IMPORTANCE OF GROUNDWATER RESPONSE TIMES FOR UNDERSTANDING CLIMATE CHANGE IMPACTS ON GROUNDWATER SYSTEMS

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ABSTRACT

Climate change can directly impact groundwater systems by altering the pattern, timing and magnitude of groundwater recharge rates. Following changes in recharge, a series of 'downstream' impacts then occur as groundwater levels and flow rates re-equilibrate to the change in boundary conditions. The timescale of re-equilibration, known as the 'groundwater response time', is a function of the hydraulic properties and geometry of the groundwater system and can vary by several orders of magnitude. This paper outlines recent research to estimate groundwater response times globally, explores how the long memory of groundwater may have played a role in human evolution and dispersal, and how understanding response times of groundwater systems is important for the management of water resources in the context of climatic change.

INTRODUCTION

A groundwater system can be viewed holistically as a complex system of interacting zones of recharge (*i.e*. the replenishment of an aquifer) and discharge (the loss of groundwater from an aquifer) mediated by the groundwater flow system, existing in a state of dynamic and often delicate balance, with multiple feedbacks (Cuthbert *et al.*, 2019) (Figure 1). The interactions between groundwater and climate are important to resolve in both space and time as they influence mass and energy transfers at Earth's land surface (Maxwell and Kollet, 2008), and are critical to sustainable water supply globally.

The possible impacts of climate change on groundwater systems are many and varied (Taylor *et al.*, 2013), but perhaps the most obvious direct impact is to the rates and timings of groundwater recharge. Such changes to recharge involve a complex interplay between land cover, soils, geology, and pumping. These effects are well studied, even if still rather poorly understood, and inadequately constrained, particularly in dryland regions (Cuthbert *et al.*, 2016; Scanlon *et al*., 2006). Less documented, however, are the nature of controls on 'downstream' impacts which occur within groundwater systems as groundwater levels and flow rates re-equilibrate after climate change impacts on groundwater recharge occur.

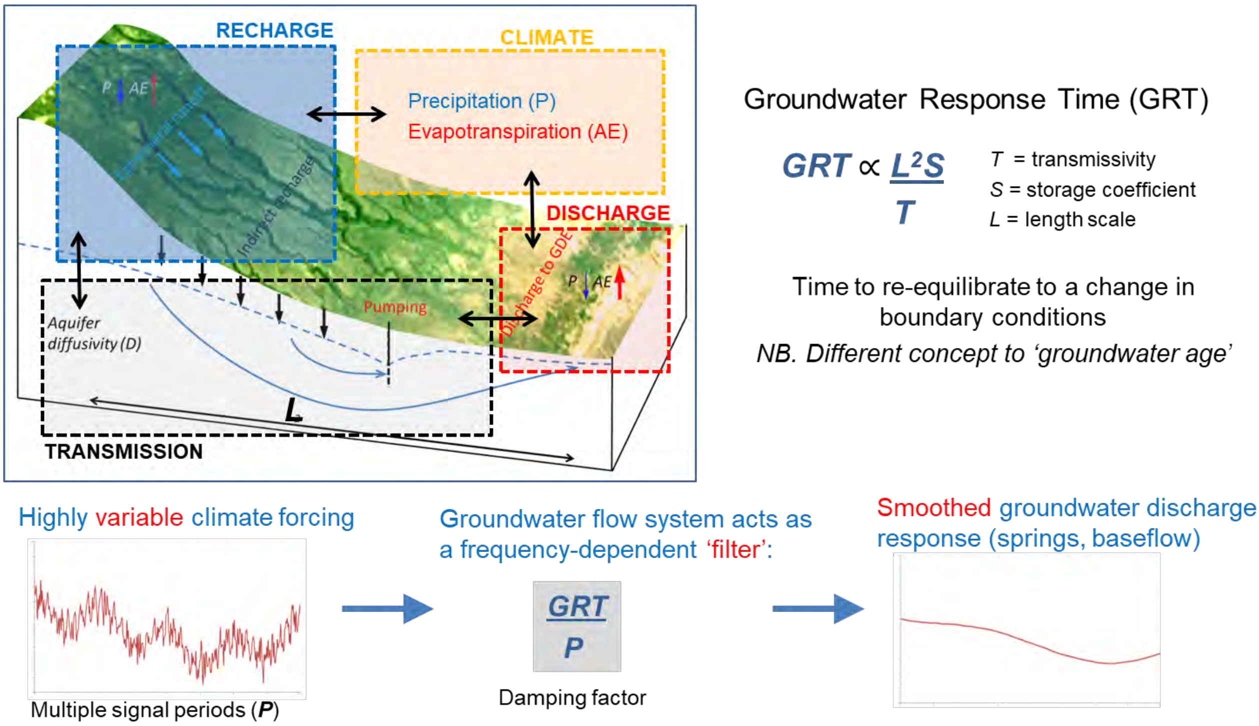

Figure 1. Climate interacts via recharge and discharge zones connected by groundwater flow systems which lag and attenuate the climate forcing on a characteristic timescale (groundwater response time).

THE LONG MEMORY OF GROUNDWATER

The length of time over which such re-equilibration happens is known as the *groundwater response time* (GRT) which depends on the hydraulic diffusivity ($D = T/S$, where T is transmissivity and S is storativity) and the length scale (L) of the groundwater flow path. This quantity is analogous to the response time of any diffusive system (*e.g.* chemical, heat, electrical). It is also known as a 'basin time constant', although this term is perhaps misleading since it is not expected to be constant in time or space (Cuthbert *et al*., 2019). The groundwater response time reflects the hydraulic response of a groundwater system (akin to the travel time of pressure waves) and should not be confused with the groundwater age or residence time which, rather, reflects the advective travel time of molecules of groundwater.

GRTs vary over several orders of magnitude depending on the length scale and hydraulic properties of the system and several situations are shown in Figure 2. Using approximate ranges for typical aquifer hydraulic properties, the groundwater response time for groundwater systems with different length scales and contexts can be derived (Table 1).

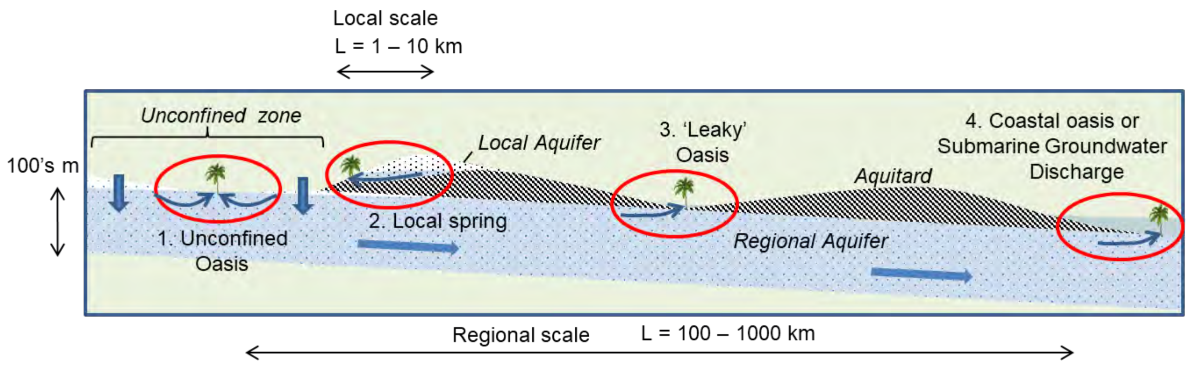

Figure 2. A schematic of some archetypal groundwater flow systems, for which typical ranges of groundwater response times have been calculated in Table 1.

	Confined systems (S<0.0001)		Unconfined/Mixed systems (S<0.01-0.1)	
Groundwater response time (Tau)	*Local scale* Months to years	*Regional scale* 10 s to 100 s years	*Local scale* 100s to 1000s years	*Regional scale* 10 000s to 100 000s years
Longest period forcings to be lagged/damped	Rainfall events Seasonal weather	ENSO/ NAO/IOD variations	Dansgaard-Oescheger (DO) cycles	Orbital climate & sea level change

Table 1. Typical ranges of groundwater response times for the archetypal groundwater flow systems sketched in Figure 2, and the sorts of periodic climate forcings that may lead to significantly dampened groundwater discharge for those systems.

GLOBAL DISTRIBUTION OF GROUNDWATER RESPONSE TIMES (GRTs)

The first global calculations for GRTs have recently been made (Cuthbert *et al*., 2019). The results show that below approximately three quarters of the area of the Earth's land surface, GRTs last over 100 years (Figure 3). As recharge happens unevenly around the world this actually represents around half of the active groundwater flow on Earth. It should be noted that these calculations have been calculated only for unconfined groundwater systems.

Nearly 50% of Earth's landmass has water tables that are strongly coupled to topography with water tables shallow enough to enable a bi-directional exchange of moisture with the climate system. However, only a small proportion (around 4% by area) of such regions have GRTs of 100 years or less, and have groundwater fluxes that would significantly respond to rapid environmental changes over this timescale (Cuthbert *et al*., 2019).

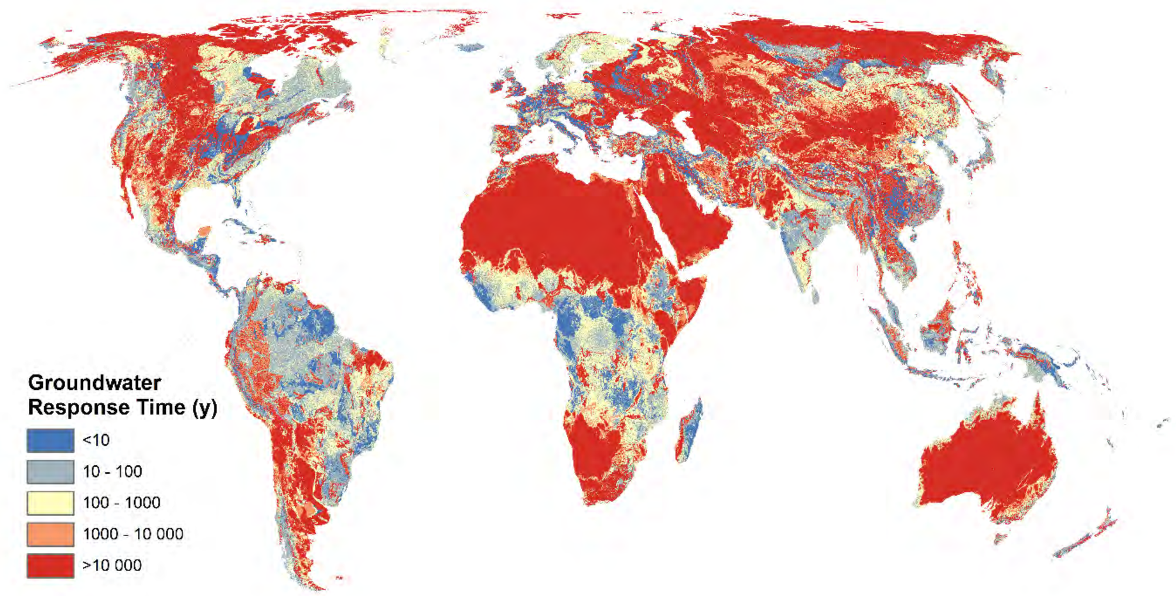

Figure 3. Global estimations of groundwater response times (Cuthbert et al., 2019), re-plotted from data freely available for download as geotiffs from https://doi.org/10.6084/m9.figshare.7393304

In general, the driest places on Earth have longer GRTs than more humid areas. This occurs because the variation of groundwater flow-path lengths (L), which dominate the magnitude of GRT, is controlled by the degree of intersection of the water table with topographic lows. Since this generally occurs more often in more humid areas, the amount of recharge effectively 'controls' the GRT, despite significant scatter due to variation in hydraulic properties (Cuthbert *et al*., 2019).

CLIMATE CHANGE, GROUNDWATER RESPONSE TIMES AND IMPLICATIONS FOR HUMAN EVOLUTION

In the modern era, the ubiquitous access to technology and available adequate energy for drilling and pumping enables humans to abstract groundwater almost anywhere it is available. However, in the distant past, the only groundwater available to our human ancestors would have been natural sources of groundwater discharge. Groundwater dependent terrestrial ecosystems (GWDTEs) are often located at such discharge zones and are directly sensitive to climate changes *via* changes in evapotranspiration. The longest groundwater pathways may be 10s to 100s of kilometres, sometimes leading to very large values of GRT (Table 1). Thus, changes in natural groundwater discharge *via* transpiration and spring flow or baseflow may therefore lag the forcing climate signal by thousands of years in some cases, and be greatly attenuated in magnitude.

The long memory of groundwater systems which makes many GWDTEs resilient to climatically turbulent periods is evidenced in the geological record, and has recently been hypothesised to have influenced the evolution of our own species (Cuthbert *et al*., 2017). For example, where key periods of human evolution are thought to have taken place in East Africa in the last 2 million years, groundwater is likely an important part of the story. Hominin stone tools and fossils have been found associated with tufa deposits which are interpreted to be fossilised springs at least 2.2 Ma old (Cuthbert and Ashley, 2014). Such fossil sites are often located near lakes, which are thought to have been saline-alkaline at that time (Cuthbert and Ashley, 2014). Thus, the springs would have been the only sources of freshwater during dry periods in the past, and would have acted as groundwater hydro-refugia – places where animals could find the necessary freshwater for survival, in an otherwise dry landscape.

Using the groundwater response concept, and the present day East African landscape as an experiment, it is possible to estimate how variable spring discharges may have been in the past under various timescales of recharge variation that were driven by climate change. The results show that some springs have the right combination of large catchments and large groundwater response times to enable spring discharges to maintain significant flows even during very long, dry periods of 100s to 1000's of years (Cuthbert *et al*., 2017).

In dry periods, there would have been intense competition for these resources and populations would have become increasingly isolated from each other. During wetter periods, springs would have enabled our ancestors and other species to migrate great distances across the East African landscape and beyond. Springs may have thus acted like stepping stones connecting other freshwater sources (rivers, lakes) and enabling mixing of populations of different species. Groundwater is therefore thought to be an important control on the movement and evolution of humans in this environment (Cuthbert *et al*., 2017).

IMPLICATIONS FOR FUTURE WATER MANAGEMENT

The 'hidden' nature of groundwater means that lag times between climate impacts on recharge and subsequent downstream impacts on groundwater discharge may be easily forgotten, in comparison to surface water resources which generally respond much more quickly and visibly to changes in climate. However the variable, and potentially slow-responding, nature of groundwater systems are critical to consider from a water management perspective. For example, while groundwater may provide an excellent buffer during drought in the short term, an over-reliance on groundwater may initially show little impact on dependent streams and wetlands, but ultimately lead to diminished flows in the longer term. It is important to realise the dynamic nature of environmental flows in this respect is when making decisions about what rates of groundwater abstraction may be sustainable. Since there may be substantial lags between changes in recharge and downstream impacts on groundwater discharge, assuming current rates of baseflow are indicative of present rates of recharge may be very misleading in some cases. Long planning horizons appropriate to the range of GRTs in a given location are thus important for water resource decision making.

ACKNOWLEDGEMENTS

I am grateful to many collaborators for developing these ideas with me and, in particular, I acknowledge the intellectual contributions of all the co-authors of Cuthbert *et al*., (2017) and Cuthbert *et al*., (2019). I am also grateful for support from the UK Natural Environment Research Council who currently fund my research through an Independent Research Fellowship.

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THE IMPACT OF THE 2015/2016 EL NIÑO ON RURAL WATER SECURITY IN ETHIOPIA

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ABSTRACT

The 2015/16 El Niño led to widespread food and water insecurity in Ethiopia, particularly in rural areas where provision of assistance is most difficult. Groundwater is considered to be a resilient source of drinking water and able to buffer inter-annual changes in rainfall. However, the performance of different types of groundwater source during extreme climate events is still poorly constrained. This current study investigates the performance and water quality of springs, hand-dug-wells (HDW) and boreholes in the districts of Kobo and Lay Gaynt in the Amhara region of Ethiopia. This paper describes new observations, including 7 rounds of water quality samples collected since the 2015/2016 El Niño. An assessment of inorganic water quality in both study areas showed concentrations above the WHO drinking water guidelines for fluoride (2% of all samples), nitrate (6%) and lead (2%). Nitrate contamination is widespread, but for the most part limited to HDWs, often with poor sanitary protection. Access to boreholes improved community resilience, however the water quality of these sources can still be impacted by geogenic contaminants and anthropogenic activities at the surface.

INTRODUCTION

Groundwater is often considered a resilient source of drinking water during times of drought and able to buffer interannual changes in rainfall (Calow *et al* 2010, Taylor *et al* 2013). However, the impact of extreme climate events on groundwater and the resilience of different groundwater sources (hand-dug-wells, springs and boreholes) during periods of stress is poorly understood. The strong 2015/2016 El Niño event caused widespread drought in the horn of Africa and in the highlands of Ethiopia seasonal rainfall totals were well below normal during June-July-August 2015. This had a considerable impact on food and water security throughout 2016 and the government of Ethiopia implemented food distribution and water tankering for those areas identified as a priority. In this study we investigate the response of different groundwater sources to drought and the resulting impact on communities. Two Woredas (districts) in the Ethiopian Highlands were identified (Figure 1) to provide a transect from high mountains through remote highland plateau to escarpment and lowland plain, Lay Gaynt and Kobo.

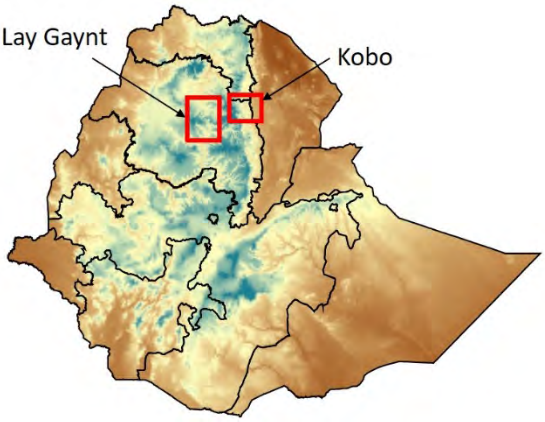

Figure 1. Location of study areas with topography.

STUDY AREAS

Lay Gaynt Woreda (Figure 2a) is split into a mountainous region to the south and remote lowlands in the north. It is located close to Mount Guna, a young (10.7 Ma) shield volcano with alkali-basalt rock type. Yields of wells can be very low when located on the shield volcanoes and dry wells are common around the Guna shield (Kebede, 2012). The lowland areas in the north have limited access to any types of improved water sources due to limited investment in infrastructure. In the highlands to the south the aquifers are mainly thin and shallow in weathered volcanic basalts or tuffs. The rhyolitic and ignimbritic nature of the rocks make them a poor aquifer, plus their topographical location means the catchment area for recharge is small and storage is low. Although rainfall is higher in this region compared to Kobo, water points often have small catchments and steep slopes, and are therefore vulnerable to drought.

Kobo Woreda is located in a low-lying, broad agricultural plain to the east of the western escarpment where a marginal graben structure runs N-S, parallel to the principal rift axis (Kebede, 2013). The plateau and escarpments are covered by trap series volcanics and the marginal graben is filled with alluvial material and lenses of lacustrine deposits (Kebede, 2013). These extensive Quaternary alluvial sediments in the valley form the main aquifer in the region and groundwater is exploited by deep boreholes for irrigation. Groundwater flow from these unconsolidated sediments is likely to be predominately intergranular with high permeability and yields. The depth of sediments can be up to 350m (Kebede, 2013). Away from the valley floor water supply is dependent on productive springs from fractured basalt. Groundwater flow from this extensive Tertiary volcanic aquifer is largely through fracture flow with reasonable yields.

Figure 2. a) Lay Gaynt woreda spring, b) Kobo woreda – alluvial plain.

METHODS

Within the two study areas a mixture of springs, hand-dug-wells (HDW's) and boreholes were identified and monitored for groundwater levels and chemistry. In total, seven rounds of water samples were collected from 50 water sources between July 2016 and November 2017. On-site measurements of temperature, pH, specific electrical conductance and alkalinity were made. Samples were analysed for major and trace elements (IC and ICP-MS), thermotolerant (faecal) coliforms and residence time indicators. Twenty of the 50 water sources were equipped with pressure transducers to collect data on water level (and abstraction) at 15 minute intervals to assess water availability, these were split evenly between the two study areas

RESULTS

The pressure transducers generated a high-resolution temporal dataset which, in combination with the social survey work, provide a wealth of information on system response and use (Figure 3). During the El Niño drought, springs were reported as being the first sources to diminish and collection times rose to 10–30 hours. In Lay Gaynt, HDWs were the most prone to failure leading to long queuing times at other sources, an eight-fold increase in the price of water and people being forced to sell livestock. Access to boreholes, which rarely ran dry, improved community resilience but Lay Gaynt has few deeper boreholes and little access to improved water sources, which led to extreme scarcity and conflict.

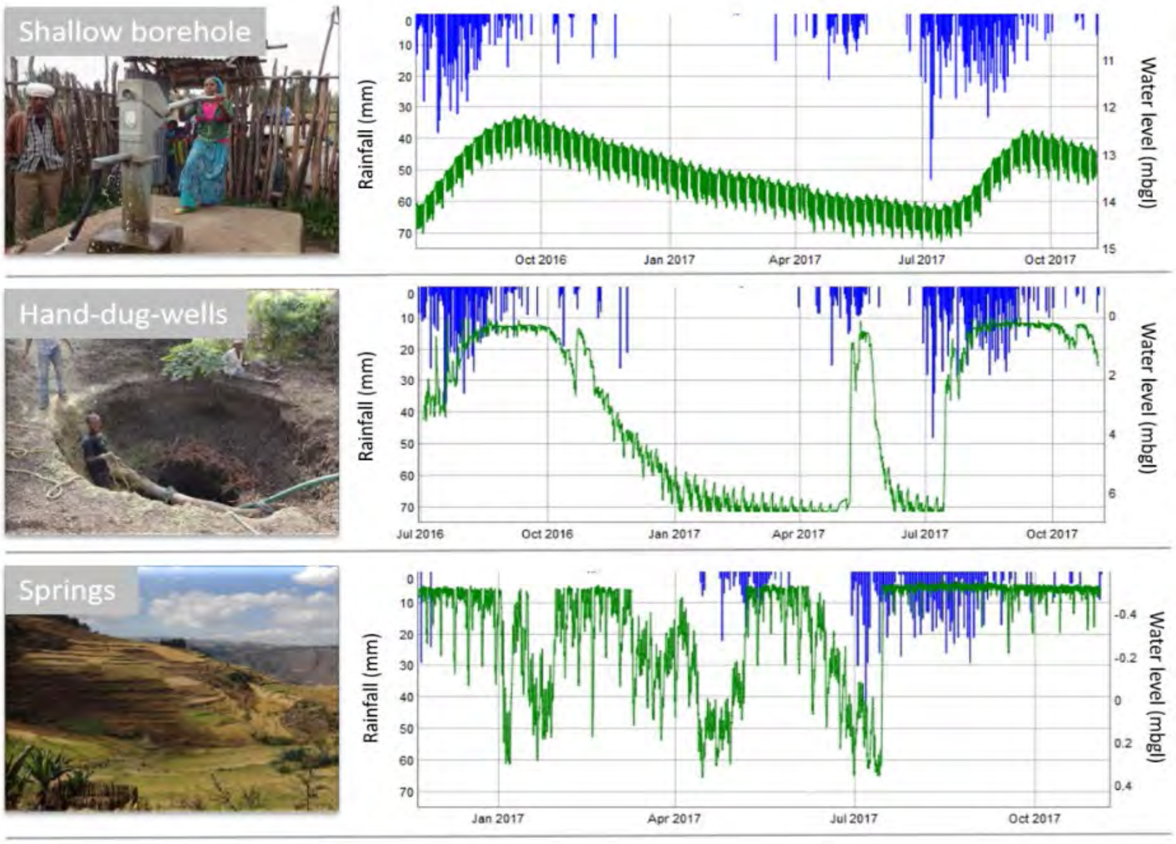

Figure 3. Example water level data from boreholes, hand-dug-wells and springs.

The groundwaters in both study areas are dominated by bicarbonate waters with a few outliers, mostly from specific sites (Figure 4). In Lay Gaynt the waters are mostly $Ca\text{-}HCO_3$ type, indicative of shallow, freshly recharged aquifers. A distinct difference between the two areas is the higher magnesium concentrations in Kobo. One of the spring sites (ELG04) discharging from Tuffs has a

Na-HCO_3 type, as have two of the Kobo sites, one a basalt spring (EKO06) and a borehole into the alluvium (EKO23). Pit latrines can be a point source of potassium/sodium for groundwaters, although if this were the case at these three sites, more temporal variability would be expected, plus corresponding increases in Cl, which aren't seen. Higher concentrations of HCO_3 and Na can also be indicative of a longer groundwater residence times, suggesting that these sites could be being fed from depth, with dykes providing a mechanism for routing spring discharge.

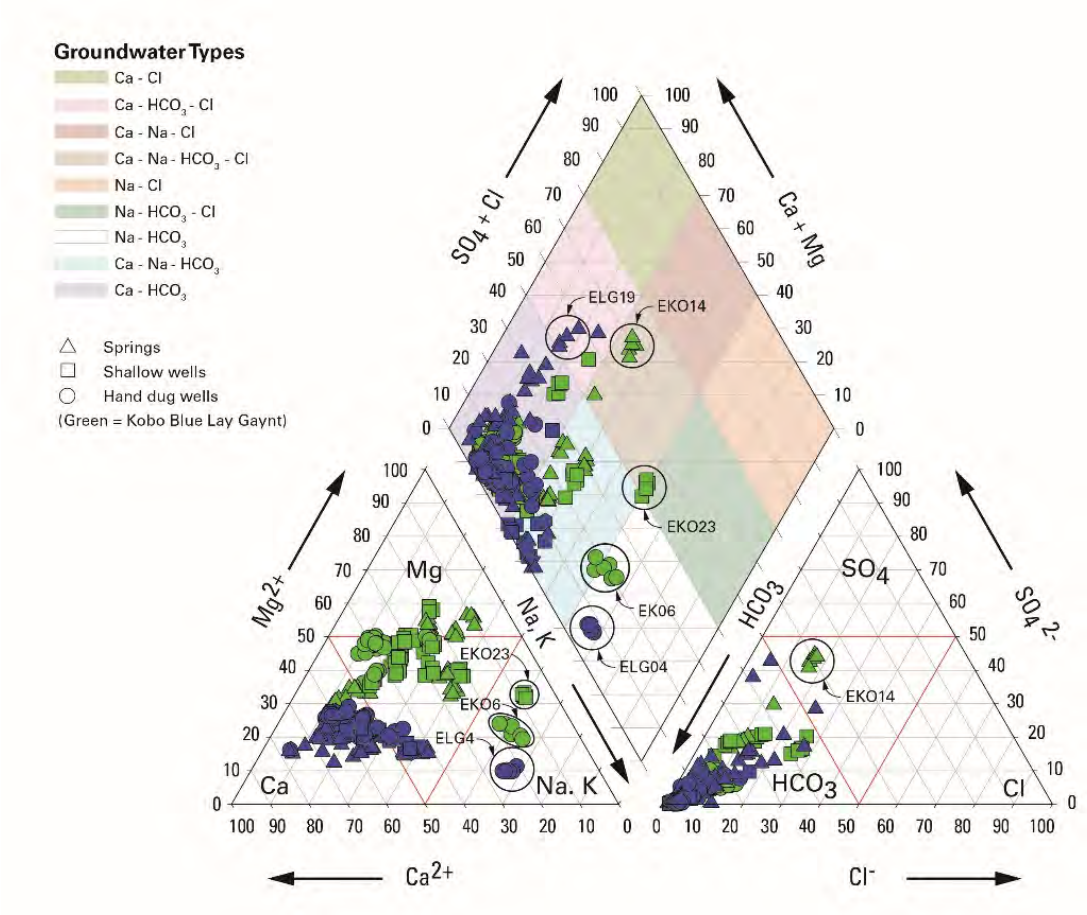

Figure 4. Piper diagram of all the sites sampled as part of the El Niño project.

An assessment of inorganic water quality in both study areas to identify where elements were over the WHO drinking water guidelines (and therefore have implications for health) identified exceedances of nitrate (6% of all samples), selenium (4.5%), fluoride (2%) and lead (2%). The issue of nitrate is widespread in Lay Gaynt, but for the most part limited to HDWs, often with poor sanitary protection. The data also highlight issues in both study areas related to reducing groundwater conditions, mobilising iron and manganese which may have implications for health. In lay Gaynt, iron and manganese are at high concentrations in HDW's throughout the area with maximum values of 3 mg/L and 2mg/L respectively and mean values of 0.13 mg/L and 0.09 mg/L, whereas in Kobo exceedances are restricted to 2 specific sites. The deeper boreholes generally show better water quality than the HDW's; in Kobo the exceedances in boreholes are for selenium only, in Lay Gaynt, where there are few boreholes, one site had high fluoride (1.7 mg/L), manganese (2.1 mg/L), zinc (5 mg/L) and nitrate (107 mg/L).

Sampling for thermotolerant coliforms (TTC's) showed widespread contamination with the greatest issues during the rainy season (Figure 5). Rapid recharge during post-drought storm events was shown to lead to a rapid deterioration in microbiological water quality, most noticeable in the shallow HDWs. Due to access and security issues during the 2017 rainy season, no samples could be collected, so it is difficult to identify if the groundwater response to the drought impacted on the magnitude of TTC's in July 2016. In general the HDW's show the highest mean TTC counts over the 18 month monitoring period and boreholes the lowest. High TTC's were observed in HDWs for at least a month after the main rains.

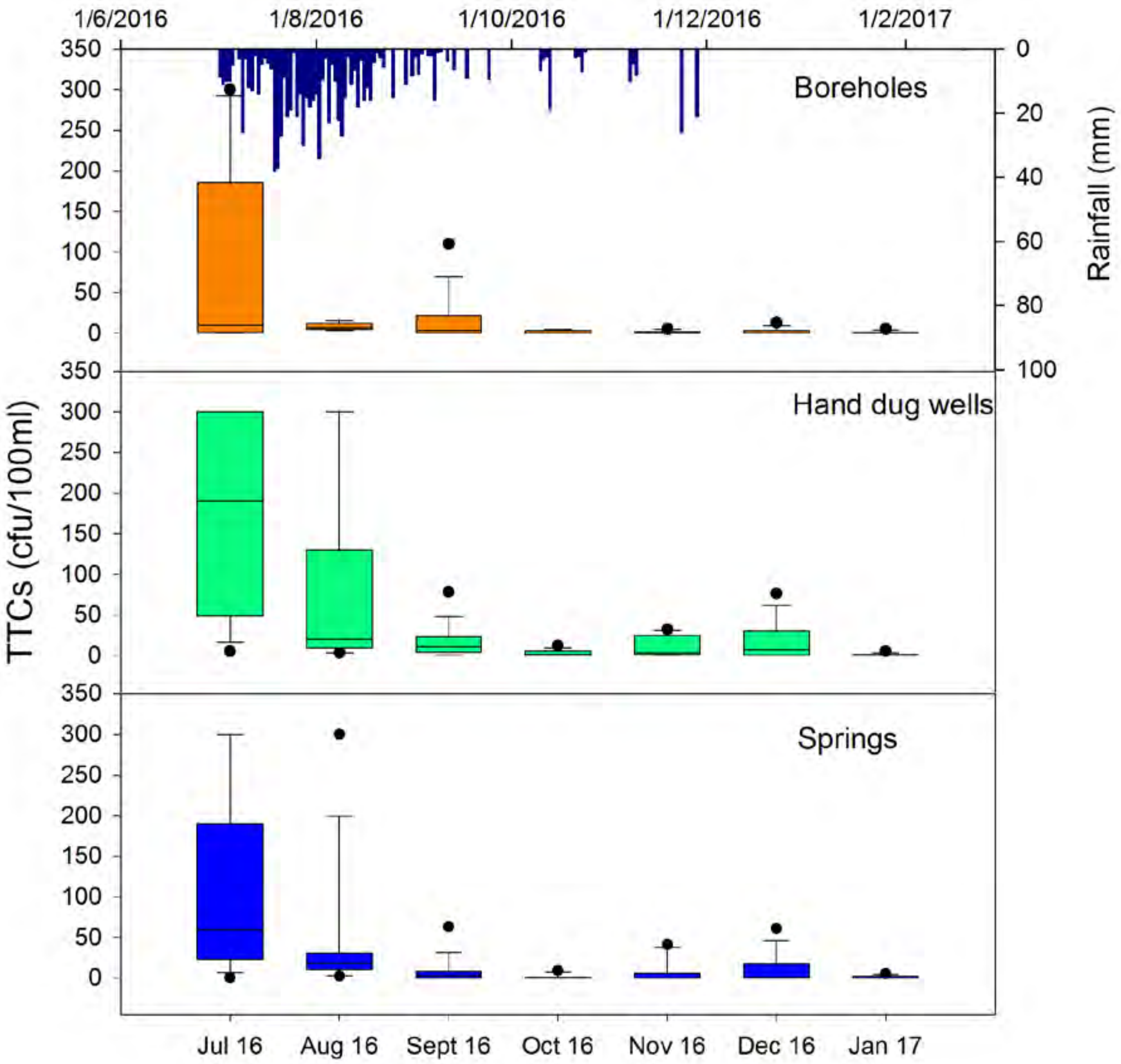

Figure 5. Time series data for TTC's in different water sources.

CONCLUSIONS

In the sources studied, all HDW's have issues with either yield (quantity) or quality. The resilience of springs was highly dependent on catchment size and in some locations were the first sources to fail. Access to boreholes, which rarely ran dry, improved community resilience, although these sources are not without their issues. All types of sources had issues with quality particularly TTCs after the end of the long drought in July 2016. Boreholes generally have better quality with lower concentrations of nitrate in these deeper sources, although elevated concentrations of selenium, fluoride and manganese are found at some sites. Lay Gaynt has few deeper boreholes and little access to improved water sources, especially in remote areas, which led to extreme scarcity during El Niño drought.

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WATER RESOURCE ASSESSMENT, E-FLOWS AND ABSTRACTION MANAGEMENT

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ABSTRACT

Ecological flows or e-flows are the river flows required to support and maintain healthy river ecology and the river's function, including its ability to provide amenity and assimilate point source and diffuse pressures. The critical metrics required to evaluate e-flows are river flow, either directly measured or modelled; the artificial influences, such as abstractions, including groundwater abstractions, diversions or discharges; the ecological condition of the river, primarily considering the biological quality elements sensitive to reduced, and sometimes increased flow, and the natural typology of river catchments.

The EPA completed an initial e-flow screening assessment to support implementation of the Water Framework Directive (WFD) in 2016, and found that abstractions may be causing an impact in up to 4% of river, 9% of lake and in 8% of groundwater bodies where abstraction could be causing an impact in associated surface water bodies. However, the abstraction dataset used for this assessment was sub-optimal, and there was also uncertainty regarding the ecological response to influenced river flows and levels in an Irish context. Legislative drivers and measures such as the 2018 abstraction registration regulations, the planned abstractions bill and the national hydromorphological work programme will facilitate more accurate assessment to formally identify any significant abstraction pressures by 2021; to support the effective management of water resources in the context of the Water Framework Directive's environmental objectives.

The formalisation of a National Hydrometric Monitoring Programme, which supports the enhanced water resource management capability of the Wallingford Hydrosolutions Qube application, a successor to the EPAs HydroTool, will enable accurate assessment of the impacts of surface water and groundwater abstractions and discharges on river flows into the future. This will provide an important foundational element in enabling the implementation of integrated catchment management and effective water sector climate adaptation in Ireland.

Key words: *Ecological flows, e-flows, low flows, drought, hydrometric monitoring, hydrometric modelling*

INTRODUCTION

Ecological flows or e-flows are defined within the context of the WFD as "an hydrological regime consistent with the achievement of the environmental objectives of the WFD in natural surface water bodies as mentioned in Article 4(1)".
Considering Article 4(1) of the WFD, the environmental objectives refer to:

- Non-deterioration of the existing status;
- Achievement of good ecological status in natural surface water bodies; and
- Compliance with standards and objectives for protected areas, including the ones designated for the protection of habitats and species where the maintenance or improvement of the status of water is an important factor for their protection,

including relevant Natura 2000 sites designated under the Birds and Habitats Directives (BHD) (EC, 2015).

Bunn and Arthington (2002) have described the fundamental elements of e-flows. The overarching logic proposes that the biota in a river or lake are adapted to all elements of the naturally present hydrological regime in the water body in which they live. The biota in a river will have adapted to thrive under a specific regime of low flow, high flow and flow dynamics of a given magnitude and frequency. Changing this flow regime is likely to be detrimental to the biology of an aquatic environment, as it will not provide suitable flows to support the various organisms present during different parts of their life cycles, and channel-forming flows in terms of depositional or erosive periods will be altered. The silting-up of salmon redds in a drained catchment being an example of such an impact. The four principles of e-flows are presented in Figure 1.

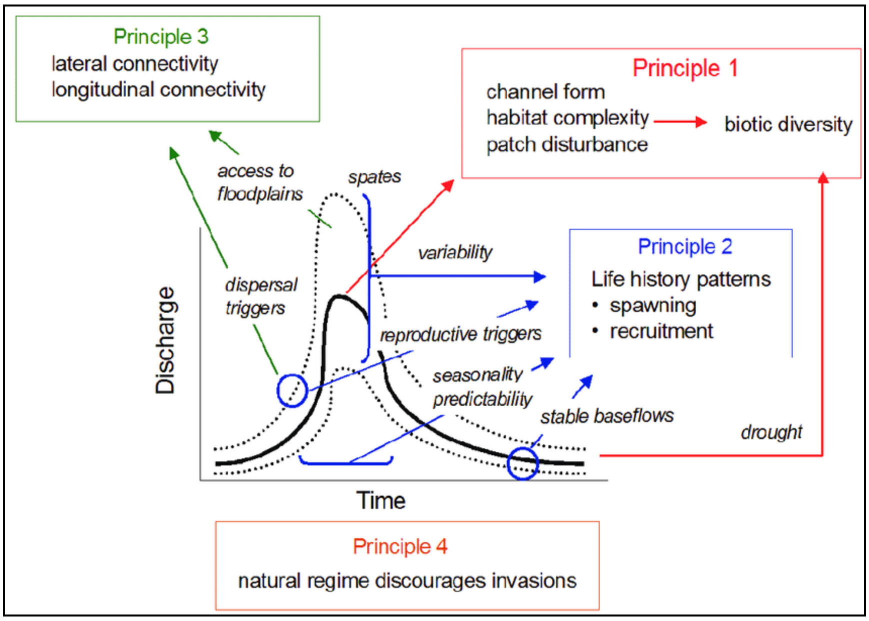

Figure 1: *Key principles to highlight the importance of the natural flow regime (Bunn and Arthington, 2002)*

Setting e-flows requires several components and is constrained by a range of factors (Webster et al, 2017). There are four main components required for e-flow characterisation including: flow regime, catchment pressures, ecology and flow paths / connectivity (Figure 2). These components must be considered in light of constraints that are, or may be present in catchments including; climate driven changes, national policies and legislation, data quality and availability, multiple stakeholders, and socio-economic factors. Groundwater abstractions are of particular importance in e-flow characterisation, as such abstractions are likely to impact on the baseflow component. The 95th percentile (Q95) flow can be considered to be essentially comprised completely of groundwater in catchments without large lakes. The Q95 is a key flow metric on which discharge and abstraction regulation is/will be based on. Therefore, the accurate characterisation and assessment of hydrogeology and the influence of groundwater abstractions is fundamentally important in establishing e-flows.

Setting and maintaining e-flows is an integral element in the effective implementation of the Water Framework Directive. While the European Communities Common Implementation Strategy (EC CIS) guidance document (EC, 2015) sets out a shared understanding of e-flows at a European level, it does not propose a uniform implementation or provide a standard protocol for the implementation of e-flows in Member States.

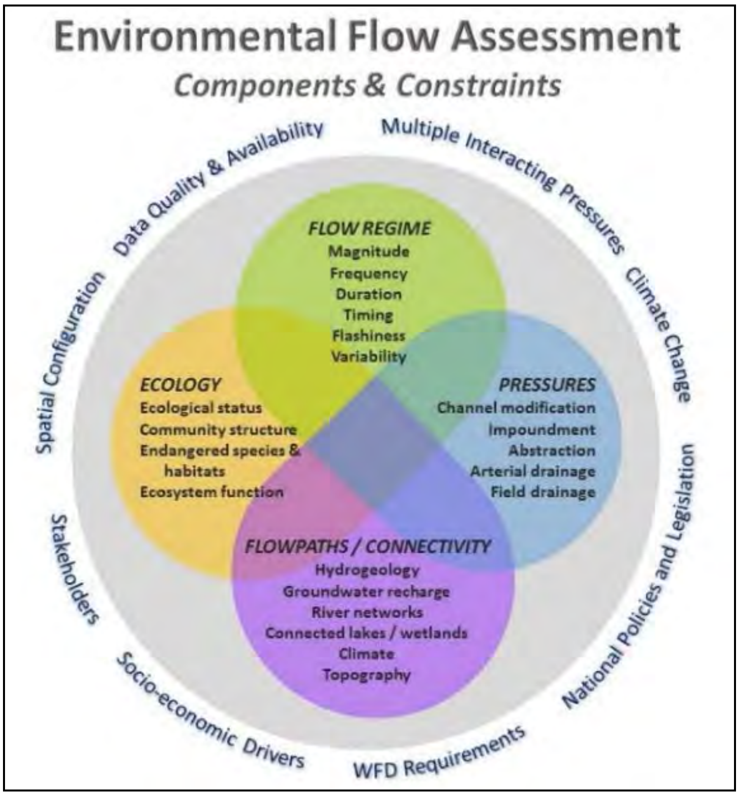

Figure 2: *Components and constraints in e-flow assessment (Webster et al, 2017)*

SETTING E-FLOWS IN AN IRISH CONTEXT

There has been limited research on characterising e-flows in Ireland. A comprehensive literature review of relevant research was completed by Webster et al. (2015) which concluded that there is presently an insufficient evidence base on which to propose bespoke e-flow standards in an Irish context at this time. This work highlighted an important research gap that remains unfilled. Specifically, an analysis of flow augmentation-driven ecological impacts in Irish river and lake habitats is required.

In the absence of bespoke Irish e-flow standards, previous screening assessments were completed using the current e-flow standards employed in Northern Ireland. This approach classifies catchments into six types based on rainfall, base flow index and catchment size (Table 1). These six river types are then grouped into three bands of sensitivity to abstraction pressure (Figure 3). When this classification method is applied to Ireland, the catchments classified as highly sensitive to abstraction pressure comprise of the upland areas and the catchments along the western seaboard. The medium sensitivity catchments are in the low-lying central and eastern parts of the country, while a small number of low sensitivity catchments are in the east of the country (CDM, 2017).

These classes, together with modelled ‘naturalised flows’ and augmented flow data, based on cumulative assessment of abstraction and discharge data and WFD waterbody objectives, are then used as the basis of a hydrological assessment of potential abstraction impact. Initially, naturalised flow duration curves (FDCs) are calculated for every river in the country. These naturalised FDCs represent the natural flow that would be in each river were all abstractions and discharges absent. This represents naturalised background conditions. The cumulative impact from headwater to catchment outflow is then modelled by adding in discharges and subtracting abstractions.

The Northern Ireland e-flow standards have been developed for high status and good status objective water bodies (Tables 2 and 3). Under these standards, when abstraction results in a reduction of the remaining water in a river below the thresholds shown in Table 2, for High Status objective water bodies (e.g. more than 5% of the Q95 of a river with a High Status objective) and in Table 3 for Good Status objective water bodies, this is classified as an exceedance of the e-flow. The overall proportion of an individual waterbody classified as an exceedance is then factored in to produce a final e-flow impact assessment result. There are drawbacks with this approach, in that it is not ground-truthed to Irish conditions, and is purely hydrological, without encompassing hydromorphological or ecological elements. However, it is conservative and therefore provides a high level of protection in terms of abstraction risk assessment and provides an appropriate initial step as a screening tool to identify waterbodies that require more detailed assessment.

The most recent screening exercise using the Northern Ireland standards, completed in 2016, concluded that there is a potential impact in up to 4% of river, 9% of lake and in 8% of groundwater bodies where abstraction could be causing an impact in associated surface water bodies. Almost all the identified abstractions potentially causing risk belong to Irish Water. The actual number of water bodies impacted by abstraction is almost certainly significantly lower than the totals identified through this screening process. Fieldwork during the 2018 drought focused on establishing actual abstraction impact in many of these waterbodies. Several hydrometric stations in the east and south of the country recorded their lowest flow on record, including a small number of stations where flows recorded during 2018 were lower than those measured during the 1976 drought. An analysis of river and lake level and flow data recorded during the 2018 drought indicates that while unabstracted waterbodies did not reach lows equalling those recorded during the 1970s, some waterbodies from which there are relatively large abstractions, did, in fact reach record lows, such as the predominantly groundwater-fed Lough Owel in County Westmeath.

Criteria for identifying types of river to which the river flow standards apply

<table>
<tr><td>Column 1</td><td>Column 2</td><td>Column 3</td><td colspan="2">Column 4</td></tr>
<tr><td>Type</td><td>Standard Average Annual Rainfall mm (period 1961-1990)</td><td>Base Flow Index (BFI)</td><td colspan="2">Catchment area (km²)</td></tr>
<tr><td rowspan="2">A1</td><td rowspan="2">< 810.5</td><td>< 0.715</td><td colspan="2">Any</td></tr>
<tr><td>≥ 0.715</td><td colspan="2">≥ 251.8</td></tr>
<tr><td rowspan="2">A2</td><td>< 810.5</td><td>≥ 0.715</td><td>< 251.8</td><td>≤ 100 (A2 headwaters)
> 100 (A2 downstream)</td></tr>
<tr><td>≥ 810.5 and < 1413</td><td>≥ 0.7495</td><td>Any</td><td>≤ 100 (A2 headwaters)
> 100 (A2 downstream)</td></tr>
<tr><td>B1</td><td>≥ 810.5 and < 1155</td><td>≥ 0.3615 and < 0.7495</td><td colspan="2">< 267.4</td></tr>
<tr><td>B2</td><td>≥ 810.5 and < 1413</td><td>≥ 0.3615 and < 0.7495</td><td colspan="2">< 267.4</td></tr>
<tr><td rowspan="2">C2</td><td>≥ 1155 and < 1413</td><td>≥ 0.3615 and < 0.7495</td><td colspan="2">< 267.4</td></tr>
<tr><td>≥ 1413</td><td>≥ 0.3615</td><td colspan="2">≥ 32.33</td></tr>
<tr><td rowspan="2">D2</td><td>≥ 1413</td><td>≥ 0.3615</td><td colspan="2">< 32.33</td></tr>
<tr><td>≥ 810.5</td><td>< 0.3615</td><td colspan="2">Any</td></tr>
</table>

Table 1: *Northern Ireland e-flow river type classification standards (DoE(NI), 2015)*

Data required to set and manage e-flows include ecological monitoring and classification, hydromorphological classification, water quality, hydrological time series, long-term flow statistics in gauged catchments and modelled data in ungauged catchments, and national abstraction and discharge data sets.

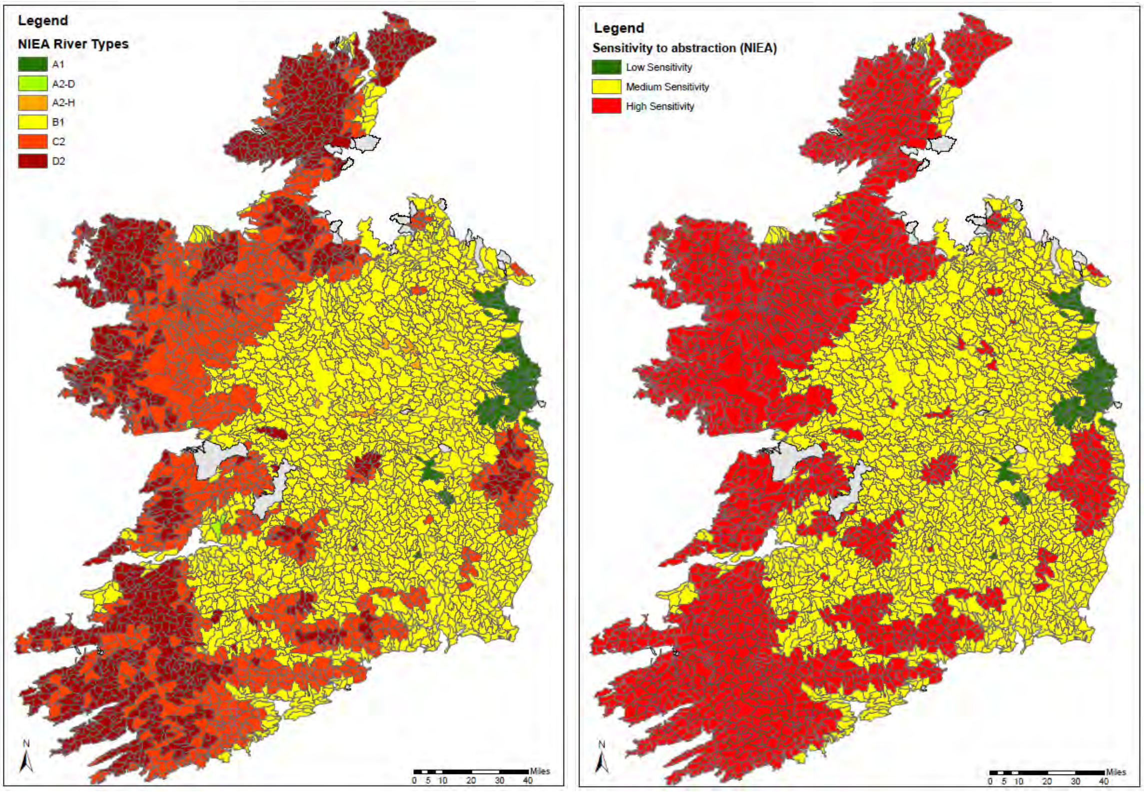

Figure 3: *River typology classification based on the Northern Ireland standards (CDM, 2017)*

High environmental standards for river flows

Permitted abstraction per day as a percentage of the natural mean daily flow(Q)[(1)]		
High		
Column 1	Column 2	Column 3
	Maximum permitted % abstraction at Q exceeding Q_{95}[(2)]	Maximum permitted % abstraction at Q **not** exceeding Q_{95}
A1, A2 (downstream), A2 (headwaters), B1, B2, C2, D2	10	5

[(1)] 'Q' is the mean daily flow for a specified period of time

[(2)] 'Qx' is the Q that is expected to be exceeded by 'x' percent for a specified period of time

Table 2: *Northern Ireland e-flow standards for High Status objective rivers based on flow percentile abstraction proportion by river abstraction sensitivity class (DoE(NI), 2015)*

Ecological, water quality and hydromorphological data is collected under the EPA WFD monitoring programme. Additional hydromorphological information such as the location and potential impact of barriers for specific aquatic species is being collected by Inland Fisheries Ireland. Abstraction data is currently being collated by the EPA via the National Abstraction Register. This register includes all abstractions >25 m^3/d. Discharge information will be collated from Section 4 discharges, wastewater treatment plant certifications and licences and from the AERs (Annual Environmental Reports) of EPA licenced facilities.

Good environmental standards for river flows

Permitted abstraction per day as a percentage of the natural mean daily flow(Q)				
Good				
Column 1	Column 2	Column 3	Column 4	Column 5
River type	Maximum % abstraction at Q exceeding Q_{60}	Maximum % abstraction at Q exceeding Q_{70}	Maximum % abstraction at Q exceeding Q_{95}	Maximum % abstraction at Q **not** exceeding Q_{95}
A1	35	30	25	20
A2 (downstream), B1, B2	30	25	20	15
A2 (headwaters), C2, D2	25	20	15	10

Table 3: *Northern Ireland e-flow standards for Good Status objective rivers based on flow percentile abstraction proportion by river abstraction sensitivity class (DoE(NI), 2015)*

The e-flow assessment will be underpinned by a robust national hydrological model. To calibrate the model, hydrometric data collected by the EPA, OPW and ESB have been used. The model is deployed in the Qube water resources management application, developed by Wallingford Hydro Solutions. This model is a refinement of the EPA HydroTool model using improved descriptor parameters and hydrometric data up to 2015. This application provides generalised modelled flows for ungauged catchments and uses local data in gauged catchments. To refine the model in areas such as controlled, impounded or karstified catchments, local spot flow data from the EPA, OPW, ESB and Irish Water will be included where appropriate.

To ensure the continued collection of accurate, regionally representative flow data to calibrate the model and to identify ongoing hydrological changes due to pressures such as land use change, anthropogenic flow augmentation and climate change, the EPA published the National Hydrometric Monitoring Programme 2018-2021 in June of 2018. This programme aims to integrate the hydrometric monitoring data obtained by these organisations to ensure there is sufficient national and regionally representative data available to complete e-flow and WFD work requiring hydrometric information. The EPA will periodically update their national flow statistics, at least every 6 years to coincide with each WFD characterisation cycle. The appropriateness of the national hydrometric network will also be assessed in each cycle. For each cycle, an updated National Hydrometric Programme will be published. In subsequent programmes, stations that have become obsolete or have otherwise fulfilled their purpose will be deactivated, and new stations may be proposed where significant data gaps in the network are identified.

Abstraction data will be obtained from the national abstraction register. Within Qube, surface abstractions will be modelled as point abstractions from the end-of-pipe abstraction point. The impact of groundwater abstractions will be modelled by calculating a stream depletion factor (SDF). The SDF is calculated using the Theis equation. The input parameters are aquifer transmissivity, storativity (Kelly, et al, 2015), abstraction rate, seasonal pumping regime and distance from the well to the nearest stream. This approach is conservative and likely to over-estimate in-stream impact from groundwater abstraction. Such a conservative approach is deemed suitable in this risk-based screening assessment based on the precautionary principle.

LEGISLATION, REGULATION AND ASSESSMENT

To underpin a risk based approach for the implementation of e-flows as set out in the River Basin Management Plan for Ireland 2018-2021, regulations establishing a compulsory national register of abstractions were enacted in August 2018. Heads of Bill for a proposed abstraction control regime legislation were open to public consultation from August 29th to October 12th 2018, and it is envisaged that this legislation will be published in the near future.

This draft legislation contains proposals to introduce a risk-based control regime governing all abstractions from surface and groundwater in Ireland. Under the Head of Bill being consulted on, general binding rules will apply to all abstractions irrespective of volume or duration, with specific general binding rules governing construction dewatering and geothermal abstractions. General binding rules include maintaining infrastructure to minimise leakage, enabling the rate of abstraction to be measured, preventing the ingress of contaminants into an aquifer and decommissioning abstractions in a safe manner, amongst other regulations. All abstractions >25 m^3/d must be registered with the EPA. All abstractions >2,000 m^3/d and all abstractions >250 m^3/d deemed to be a significant pressure to an “at risk” waterbody will be required to obtain a licence. The EPA will be responsible for maintaining the register of abstractions, completing the abstraction impact assessment, and is proposed as the authority for licencing abstractions where necessary. The proposed legislation does not account for impoundments and it is not proposed to regulate such features at this time. The impact of impoundments on water body ecology will be assessed under WFD hydromorphology characterisation.

Under the proposed abstraction impact assessment procedure, the abstraction control regime Heads of Bill implies that existing abstractions will be treated differently to new abstractions. Where existing abstractions are deemed to be potentially causing risk, the intention will be to licence them with a longer term aim of sourcing a more sustainable permanent alternative. New abstractions will be assessed using the Qube application. All new registrations will be added to the model, which will also incorporate new discharges, as they become known to the EPA.

The precise conditions that will trigger the requirement for a licence will be determined under the finalised legislation. One potential assessment procedure being considered could consist of an analysis of the predicted new augmented flow in a catchment that will be present once a proposed abstraction becomes active. All abstractions could initially be analysed based on a maximum and permanent abstraction volume as per their registration. The predicted augmented flow could then be compared to the calculated e-flow for the catchment in question, and in all downstream waterbodies to identify any potential e-flow exceedances using the Qube application. If the proposed abstraction brings the predicted augmented flow below or to within a certain proximity to the calculated e-flow, then a more detailed assessment may be required.

CLIMATE CHANGE ADAPTATION

Current predictions of future climate-driven changes on Irish hydrology and hydrogeology are based on a relatively small body of research and there is a high level of uncertainty in these predictions, particularly regarding changes in precipitation patterns and the frequency, duration, and magnitude of droughts. Research efforts need to be focused on providing robust predictions of future changes and likely regional variations in such changes. This research and effective adaptation planning will be supported by: a) maintaining a nationally and regionally representative long-term hydrometric and groundwater monitoring networks to provide baseline data for ongoing modelling, and to identify where predicted changes are or are not emerging, and to measure the magnitude of such changes, b) incorporating up to date hydrometric and groundwater data in subsequent WFD characterisation cycles to identify water bodies at risk from abstraction pressures due to climate driven changes in river flows and groundwater levels and c) operating a sufficiently dynamic, risk-based abstraction licencing system that facilitates pro-active regulation of the aquatic environment in the face of climate driven changes to river flows and groundwater resources in accordance with WFD characterisation in future.

Recent research (Noone, et al, 2017) has indicated that most of our existing long-term flow statistics are likely to have been recorded during an atypically wet period when compared to the entire historical climatological record. If this is the case, it is likely that our current low flow statistics over-estimate long-term historic low flows. As predicted climate driven changes to low flows indicate that these longer term low flows are likely to reduce by >20% in future, this indicates a requirement for a dynamic and pre-emptory water resources management regime to sustainably adapt to such changes, protecting our aquatic environment and providing for the need of our population in a sustainable manner. The predicted impacts of climate change on low flows in Ireland are particularly relevant to sustainable groundwater resource use and protection, as the reduced river baseflows predicted under such scenarios mostly comprise of groundwater discharge. Therefore, any future climate-driven river flow changes will likely require reductions in permitted abstraction volumes and will therefore reduce permissible available surface water and groundwater resources in the coming decades.

CONCLUSIONS

When fully operational, the abstraction assessment and licencing system will result in an applied e-flow methodology that will be as simple as possible, transparent, consistent, and capable of integrating future advances in our regulatory systems and the scientific understanding of the links between hydrology and ecology in our rivers. Fundamental gaps remain in our knowledge of the links between ecology, hydrology and hydrogeology in various Irish landscape settings, aquifer and river types. Also, any such system has the long-term potential to become integrated with licencing and enforcement databases, with abstraction and discharge data automatically updated from annual environmental reports for example. In any case, this evidence-based, risk-based, forward-looking approach will enable the EPA to provide, within an integrated catchment management framework, a high level of environmental protection and regulatory efficiency in the task of estimating the available surface and groundwater resources nationally into an uncertain future.

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GROUNDWATER STORAGE AND TRANSMISSION IN IRISH AQUIFERS – IMPLICATIONS FOR YIELD SUSTAINABILITY

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ABSTRACT

Groundwater storage and flow properties in Irish bedrock aquifers are dominated by secondary, fissure porosity and permeability. Primary porosity and intergranular permeability are, in the main, only found in the unconsolidated sand and gravel aquifers that were formed by glacial or post-glacial processes. This paper summarises the controls on aquifer storage and transport parameters, and examines the implications for borehole yield sustainability.

1. INTRODUCTION

Abstractions from some boreholes in fractured aquifers are known to struggle to yield sufficient water volumes either seasonally or during prolonged dry weather. For example, the public supply at Banagher in Co. Offaly can provide more than 400 m^3/d for much for the year, and even up to 700 m^3/d for short periods. However, during late summer and early autumn, the maximum abstraction rate can drop off significantly, to less than 150 m^3/d. This is due to overall falling groundwater levels in a low storativity aquifer, combined with a lack of fissures within the main volume of the aquifer connected to the main flowing fault zone. At Shinrone, also in Co. Offaly, a borehole was tested at a high, but unsustainable, rate, resulting in a significant increase in drawdown once the main flowing fissure intercepted by the borehole was dewatered. Low storativity in the limited number of confined aquifers (e.g. Tydavnet, in Co. Monaghan, Bog of the Ring, in Co. Dublin, or Fardystown in Co. Wexford) also plays an indirect role; here transmissivities are high, but there is very little storage, resulting in rapid water level declines when pumped at high rates indicated by the initial pumping tests.

Productive zones within aquifers are generally associated with fault zones, and relatively high abstraction rates can be achieved if fault zones are intercepted by a borehole. However, due to very limited storage within Irish fractured aquifers, yields are only sustainable if a connected network of fissures exists to provide groundwater flow to the higher permeability fissure. The network of smaller fissures, if present in the aquifer, may dewater partially or fully due to seasonal groundwater declines, or local water level decreases due to pumping. This will result in a dramatic drop-off in borehole yield. This illustrates the importance of undertaking test pumping for a sufficient duration, and at the appropriate time of year.

2. NATURE OF IRISH AQUIFERS

2.1 BEDROCK AQUIFERS

Bedrock aquifers in the Republic of Ireland do not exhibit significant intergranular permeability or porosity apart from a very few exceptions[1]; fissure permeability is the dominant type of permeability and porosity. Most fissures are a result of earth movements causing breaks in the rock, although they

[1] The main exception is the Kiltorcan-type sandstone in which there is limited intergranular permeability and porosity. Separately, in dolomite aquifers, an approximation to intergranular groundwater flow can occur in localised patches.

can originate from a variety of processes. The development of fissure permeability and porosity in bedrock in Ireland depends on several factors, including structural history, the potential for karstification and dolomitisation, and depth below the top of the rock surface.

Of main significance to the development of fissure permeability and porosity is the frequency of fracturing and the degree to which the fracturing is open to water movement. These are, in turn, influenced by factors including the intensity of the structural stress, the rock type, the depth of burial at the time of deformation, the orientation of stress and the bedding thickness. Current understanding of these factors and their influence on the regional distribution of fracture patterns is outlined in Dunphy (2003), Fitzsimons *et al.* (2005), Moore and Walsh (2013) and Geological Survey Ireland (in prep.).

Our understanding of Irish bedrock aquifers rests on the observations and descriptions of a number of hydrogeologists working in Ireland, starting with David Burdon. Fitzsimons *et al.* (2005) summarised the different fracturing with depth and associated transmissivity in well-fissured and poorly-fissured bedrock aquifers. Daly and Hunter Williams (2008) summarised the conceptual models for groundwater flow paths typically active in fissured bedrock aquifer catchments, noting four groundwater flow pathways: (1) interflow [in subsoils and the weathered top of bedrock], (2) shallow groundwater flow, (3) deep groundwater flow, and (4) discrete fault or conduit flow. Work undertaken by the Pathways Project (Archbold *et al.*, 2016) and Poorly Productive Aquifers Project (e.g. Comte *et al.*, 2012; Cassidy *et al.*, 2014) developed the understanding further, and Kelly *et al.* (2015) summarised the three bedrock groundwater flow pathways as shown in **Figure 1**.

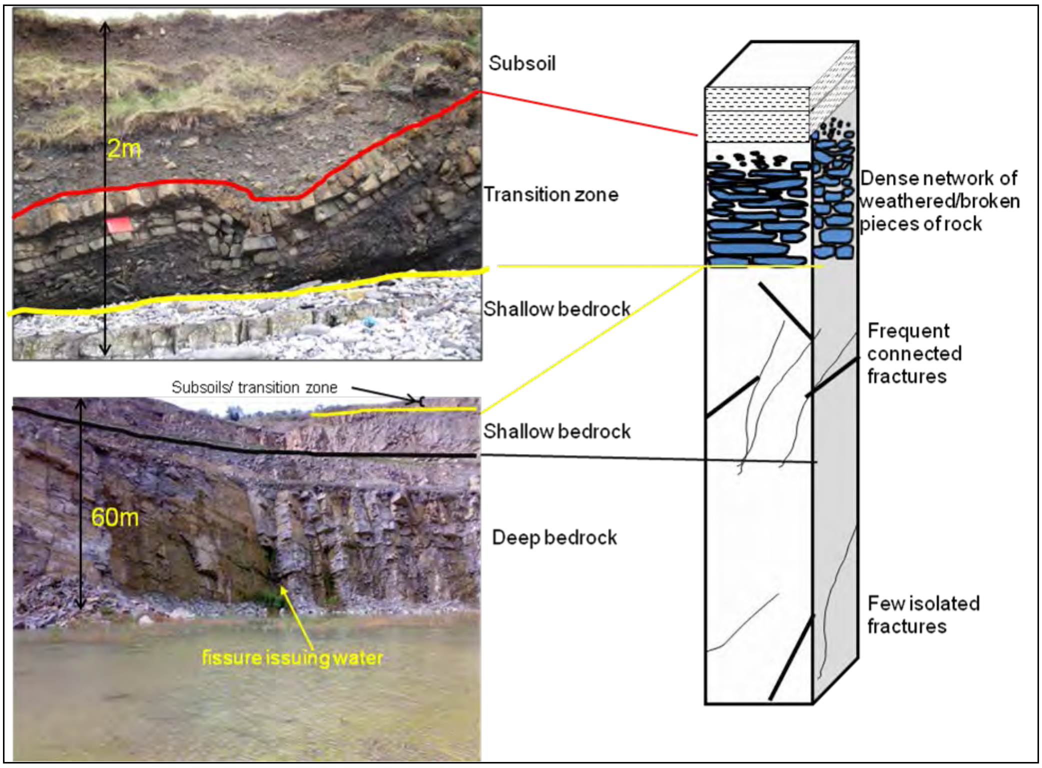


Figure 1. The main groundwater flow pathways in Irish fissured aquifers (from Kelly *et al.*, 2015).

1) *Transition zone*. This zone of broken and weathered rock is located between the subsoil and competent unaltered bedrock. It usually extends to within 1 m to 2 m of the top of rock but can rapidly change in thickness over very short distances and may be absent, particularly where ice scour has been significant. In contrast, the zone can be over 10 m thick in places where inter-glacial weathering or frost shattering has been particularly intense, and area has been protected from subsequent erosive processes (Blake *et al.,* 2016; Tedd *et al.*, 2017). As a pathway, where it is present, it is generally more permeable than the underlying bedrock. Fissure permeabilities and transmissivities in this zone

are expected to be similar across most rock types. However, in shalier bedrock units the transition zone can be difficult to distinguish from subsoil and the underlying bedrock. Flow and fissure permeability may be as high as those of 'dirty' gravels in certain situations. Examples of the transition zone can be found on GSI's website[2].

Groundwater will flow in the transition zone in areas of lower ground, during high or persistent rainfall events, and where the aquifers are poorly productive. Groundwater may be perched or in continuity with groundwater in fractures below. When saturated or partially saturated, it is a significant pathway for groundwater flow (Fitzsimons *et al*., 2005 and Daly and Hunter Williams, 2008) and nutrient delivery (Archbold *et al.*, 2016) in Ireland. Comte *et al.* (2012) found at their study sites approximately 50% of groundwater flow in poorly productive aquifers occurs in the transition zone and that the zone plays a crucial role in sustaining surface water and related ecosystems.

The transition zone will often be periodically dry, so it is not a reliable groundwater resource and will contribute to groundwater spring or borehole flow only when it is saturated.

2) and 3) *Shallow and deep groundwater flow zones.* Fitzsimons *et al.* (2005) summarised the conceptual models for Irish bedrock aquifer permeability variation with depth, and implications for transmissivity as a function of water table elevation within the aquifer (**Figure 2**). In poorly productive aquifers (**Figure 2, right**), connected fissures and fractures are not developed to a significant depth, and the majority of groundwater flow is shallow. However, significant groundwater flows can occur in isolated fractures at depth if they are present (and also in the Transition Zone if it is saturated or partially saturated). In productive fissured aquifers (**Figure 2, left**), fissuring is well-developed and connected to a greater depth within the aquifer. In these aquifers, there can also be isolated productive fissures at greater depths. However, the relative contribution of groundwater flow tends to be much less significant than in poorly productive aquifers.

Where the groundwater level falls below the base of the zone of more interconnected fissuring, either locally due to a cone of depression developing around a pumping borehole, or more broadly due to seasonal changes, the transmissivity and the yield will drop off significantly.

As well as vertical variations in permeability and transmissivity, there are significant lateral variations due to the heterogeneity imparted by fissuring and faulting. **Figure 3** shows schematically the difference in potential yield from boreholes sited in fault zones in **(A)** and (**B**) poorly fissured, poorly productive aquifers and (**C**) well-fissured, productive fractured bedrock aquifers. The sustainable yield is different because although individual fault zones may be highly transmissive, a connected fracture network is required to sustain groundwater flow from the aquifer to the fault zone. If this is lacking, an initially high-yielding borehole will dewater to below the base of the main feeder fractures, and yield will drop off quickly.

[2] https://www.gsi.ie/en-ie/programmes-and-projects/groundwater/projects/gw3d/Pages/Transition-Zone.aspx

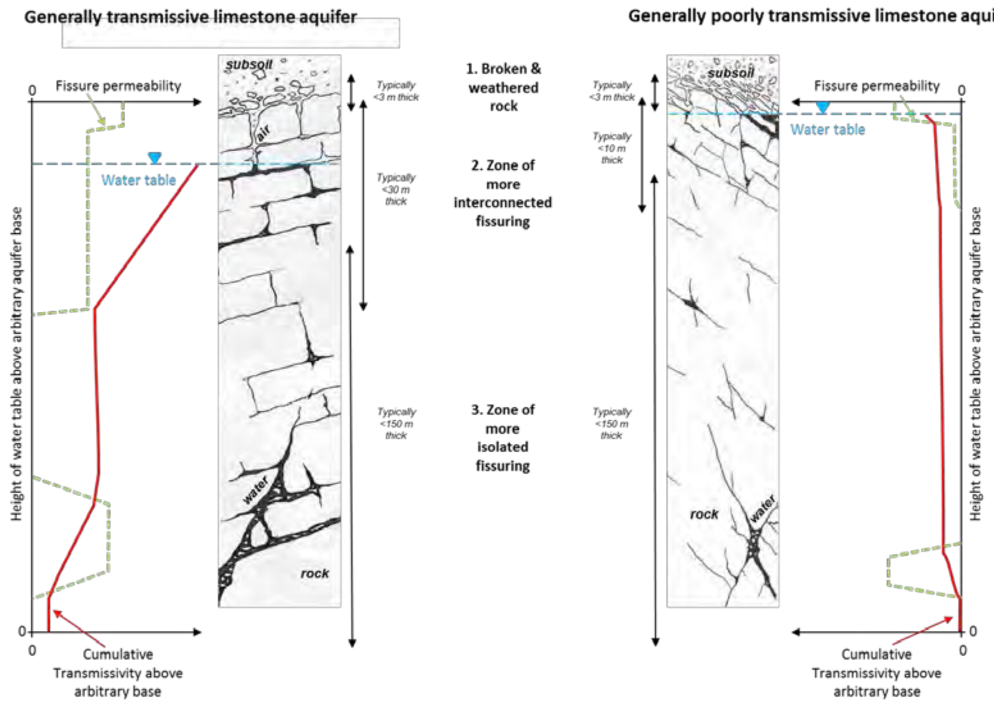
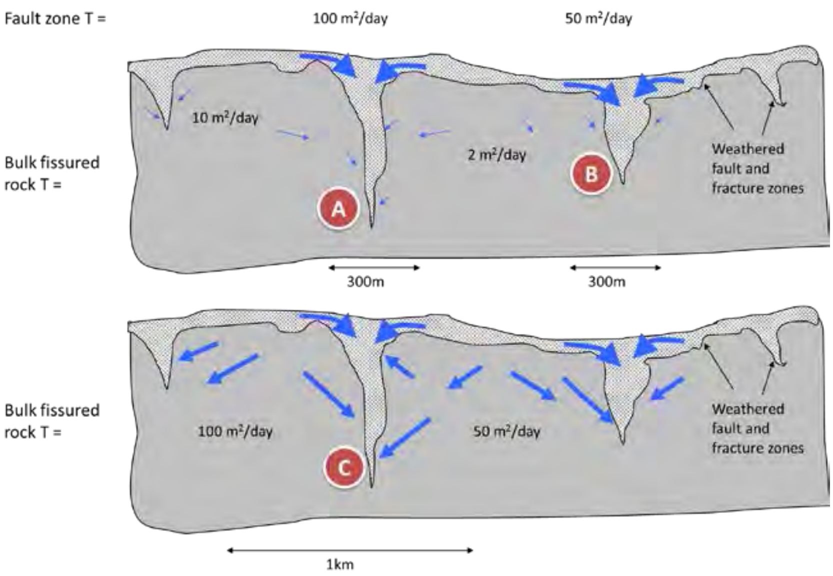


Figure 2. Conceptual variation of transmissivity and fissure permeability with depth in two hypothetical aquifers. Adapted from Fitzsimons *et al.* (2005). Note that Zone 1. Broken & weathered rock is the Transition Zone.



A 3 km long fault zone with 300 m wide enhanced fissuring zone of 100 m^2/d transmissivity. Theoretical yield **600 m^3/d**

B 0.5 km long fault zone with 300 m wide enhanced fissuring zone of 50 m^2/d transmissivity. Theoretical yield **100 m^3/d**

C 3 km fault zone with 300 m wide enhanced fissuring zone of 100 m^2/d transmissivity in productive fissured bedrock aquifer of 50-100 m^2/d transmissivity. Theoretical yield **2,000 m^3/d**

Annual recharge of 250 mm in all cases

Figure 3. Schematic illustration of potential sustainable yields from different transmissivity fault zones in generally poorly productive fissured aquifer (upper) and productive fissured aquifer (lower). From GSI (in prep.) and adapted from images and calculations by Vincent Fitzsimons.

2.2 SAND AND GRAVEL AQUIFERS

Sand and Gravel aquifers are very different from almost all the other Irish aquifers, in several ways: they are much younger, they are uncemented, they are essentially unaffected by folding, faulting or fracturing, and their permeability is intergranular rather than fissure-dependent. Irish gravel aquifers were deposited during the Quaternary period of our geological history, i.e. within the last 1,600,000 years, or what is commonly known as the Ice Age. During this period Ireland was subjected to a number of glaciations, interspersed with warmer spells (interglacials). Most Quaternary deposits in Ireland were laid down during the last glaciation, which took place from about 70,000 to 10,000 years ago. The deposits can be broadly classed as:

- Glacial: deposited more or less directly from the ice, therefore relatively unsorted and less permeable.
- Glacio-fluvial: deposited by running water beneath or downstream of the ice, therefore better sorted and more permeable.

Since the last glaciation ended about 10,000 years ago, other sand and gravel deposits have been laid down by rivers and along the coast. As a result of these glacial and post-glacial geological processes, sand and/or gravel aquifers in Ireland are found in a variety of geological environments (Creighton, 1981), including: Outwash deposits, Eskers, Moraines, Buried valleys, Alluvial gravels and river terraces (**Figure 4.A),** Dunes, and Raised beaches.

The aquifer properties of sand/gravel aquifers can be predicted with some reliability, based on their basic properties of grain size, sorting and aquifer thickness. Higher permeability is favoured by larger grain size (i.e. coarser material) and by better-sorting of the material. Greater saturated thickness of permeable layers produces higher transmissivity. Glacial deposits (deposited directly from the ice) are relatively unsorted and less permeable (**Figure 4.C**), whereas Glacio-fluvial deposits (deposited by running water beneath or downstream of the ice) are better sorted and more permeable (**Figure 4.B**).

A. Terrace sands and gravels, Bandon River System, Inishannon, Co. Cork

B. Esker sands and gravels, Kilkelly, Co. Mayo

C. Moraine sands and gravels, Mountbagnall, Co. Louth

Figure 4. Example of the internal sedimentary architecture of sand and gravel deposits with different origins. (Photos from GW3D project, GSI.)

An important factor is the continuity of permeable layers, or the presence of low permeability layers between coarser-grained horizons: where the coarser deposits are in discrete lenses separated by less permeable silts and clays, continuity is impeded and development potential is reduced. In aquifers where there are low permeability layers, vertical permeability is orders of magnitude less, recharge may be restricted and development potential impacted. Horizontal layering or interfingering with lower permeability sediments can occur particularly in buried valleys, alluvial deposits and at esker margins.

The development potential of the different types of sand/gravel aquifer vary considerably because of their differing extent, thickness and permeability. Recharge to gravel aquifers in Ireland is normally high, owing to high infiltration capacity at surface. High effective porosity and storativity usually ensure a dependable supply even from quite small aquifers. Water level fluctuations, whether in response to rainfall or over the annual cycle, tend to be rather small and subdued. However, thin gravel aquifers can be very sensitive to induced changes in water level.

3. TRANSMISSIVITY AND STORAGE IN IRISH AQUIFERS

Although there is a lot of activity in the hydrogeological sector within Ireland, there are relatively few aquifer parameter data readily available, in particular when considering aquifer storage properties.

Kelly *et al.* (2015) collated available porosity, specific yield, storativity, permeability and transmissivity, and presented the summary data in the GSI/EPA ‘Aquifer parameters report’. The data are included in a detailed database and are representative, in the main part, of significant aquifer volumes. (There are a small number of data obtained from packer testing and falling/rising head tests, which would represent a volume on the order of cubic metres.) Also included in the database were specific yield values derived from hydrographs (e.g., Tedd *et al.*, 2012).

Core-scale permeability and porosity were measured as part of the investigations into the feasibility of Carbon Capture and Storage in the sedimentary basin near to Moneypoint power station in County Clare (Farrelly *et al*., 2010). Whilst data from this scale of measurement are not representative of groundwater flow and transport in fractured aquifers, it is interesting to see what aquifer parameter values are associated with the rock matrix, as opposed to the fractures.

3.1 AQUIFER STORAGE

In the Aquifer Parameters database (Kelly *et al*., 2015), there are 86 records available for confined storage coefficient and unconfined specific yield in bedrock aquifers. Unconfined and confined aquifer storage values are relatively consistent across all of the aquifer categories for which there are data (**Figure 5**). The average bedrock specific yield is 0.01 (1×10^{-2}) and the average confined storage coefficient is in the order of 0.00011 (1.1×10^{-4}). The values compare well with ranges for specific yield of 0.01 to 0.06 (diffuse karst ‘Rk^d‘ aquifers) and 0.03 to 0.04 (Locally important ‘Ll’ aquifers) reported in Tedd *et al.* (2012) for bedrock aquifers in the Southeastern region.

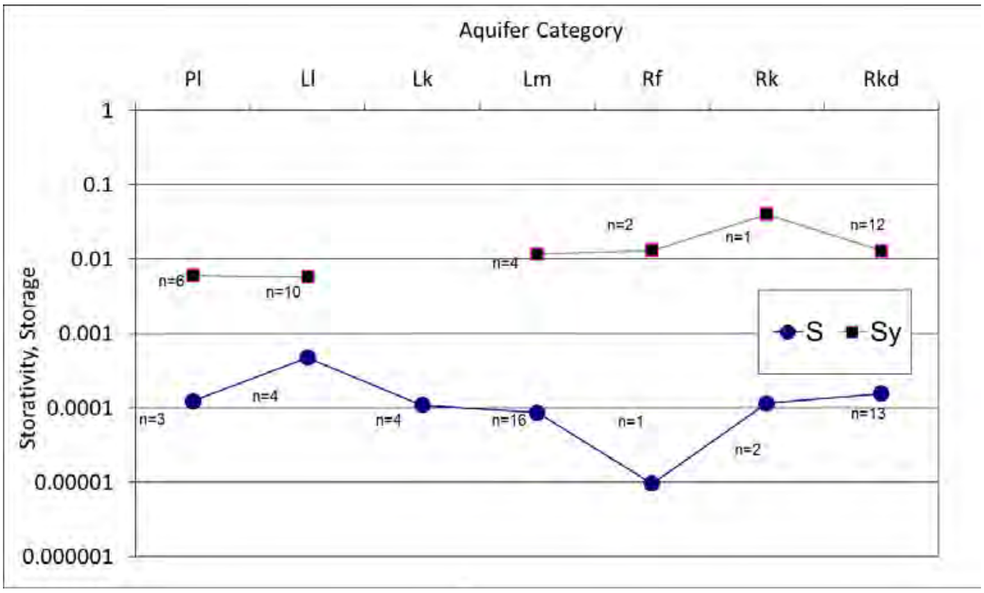


Figure 5. Geometric mean for confined storage coefficient and specific yield across the bedrock aquifer categories represented. From Kelly *et al.* (2015)

There are few data available for sands and gravels. **Table 1** summarises values reported in Kelly *et al.* (2015).

Table 1. Summary of storage parameters in sand/gravel aquifers

Specific yield (Sy)	Storativity (S)	aquifer, location, data origin and information source
0.13–0.19		Glacio-fluvial sand and gravel aquifers in the southeastern river basin district. Sy derived from analysis of groundwater level hydrographs. Tedd *et al.*, 2012.
0.13		Glacio-fluvial sand and gravel aquifer, Curragh, Co. Kildare. Pollardstown Fen. Sy derived from pumping test. D. Daly (1981).
0.19		Glacio-fluvial sand and gravel aquifer, Curragh, Co. Kildare. Sy derived from groundwater recharge modelling. Misstear *et al.*, 2008
0.1		Glacio-fluvial sand and gravel aquifer, Ardtully Beg, Co. Louth. Sy derived from pumping test. An Foras Forbatha/GSI, 1982.
0.04 to 0.08		Glacio-fluvial/riverine sand and gravel aquifer, Arklow, Co. Wicklow. Sy derived from pumping test. White Young Green (2009)
	0.0003 ($3x10^{-4}$) to 0.003 ($3x10^{-3}$)	Glacio-fluvial sand and gravel aquifer, Robertstown, Co. Kildare. Test pumped. K.T. Cullen (2001).

In comparison, at the core scale, maximum non-weathered porosity recorded by Farrelly *et al.* (2010) was 1.5 %, with average limestone porosity 0.775 %, and sandstone average porosity 0.57 % (**Figure 6**). Cores from the Burren Formation and other Dinantian limestones, and Upper Carboniferous sandstones in Southeast Co. Clare were assessed. Farrelly *et al.* (2010) note that the results for the Ross Sandstone Formation appear consistent with petrographic observations undertaken by UCD, which "show that the sandstones contain a quartz cement that serves to anneal the internal porosity and permeability. Similarly poor porosity and permeability results for the Dinantian Limestone succession are considered to be representative of tight limestones in which the porosity has been filled by carbonate cements.”

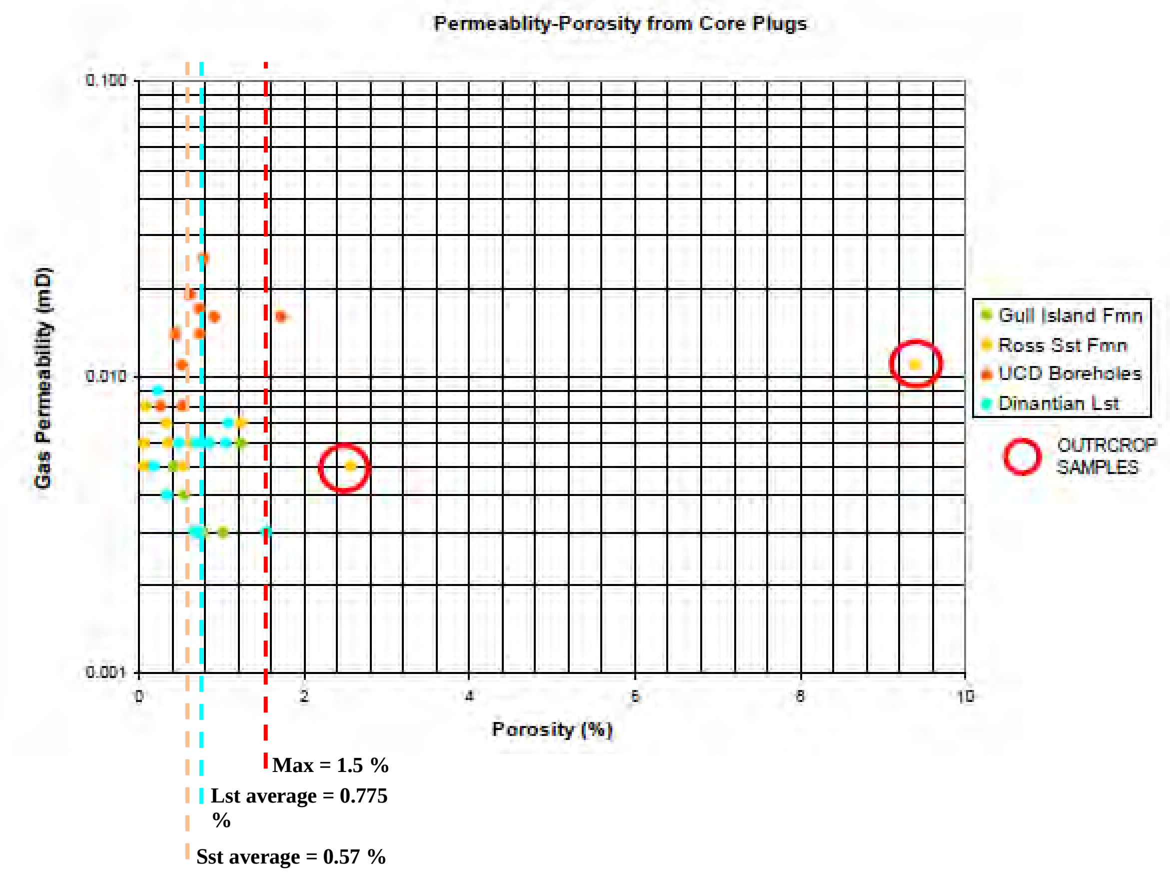


Figure 6. Permeability versus porosity plot for project and UCD data sets (outcrop samples highlighted). Fmn (formation), Sst (sandstone), Lst (limestone). Adapted from Farrelly et al. (2010).

3.2 AQUIFER FLOW

There are more than 2,300 transmissivity data in the GSI/EPA Aquifer Parameters Database (2,280 bedrock, 31 sands gravels). However, the majority of these are bulk values for the total depth of the borehole. This means that any vertical variation of bulk permeability with depth, or fissure permeability, cannot be determined.

Permeability data are much more limited. The Aquifer Parameters database contains only a small number of depth-dependent bulk permeability data. These are clustered around the Dublin area from major infrastructural developments such as the Metro, Port Tunnel and Interconnector, and therefore may not represent permeability values or variations nationally (**Figure 7**). Comte *et al.* (2012) undertook detailed work at three sites in poorly productive fissured bedrock aquifers, and found that bulk permeability decreased with depth (**Figure 8**), with a geometric mean permeability in a Pl aquifer transition zone of 0.09 m/d, shallow bedrock 0.016 m/d, and deep bedrock 0.0012 m/d (shown as red dots on **Figure 7**). Air permeability measurements made on cores approximate to 0.003 – 0.004 m/d permeability to water (**Figure 6**, Farrelly *et al.*, 2010). This indicates that there is very little fracturing or fissuring in the ‘Deep Bedrock’ zone at some of the sites assessed by Comte *et al.* (2012).

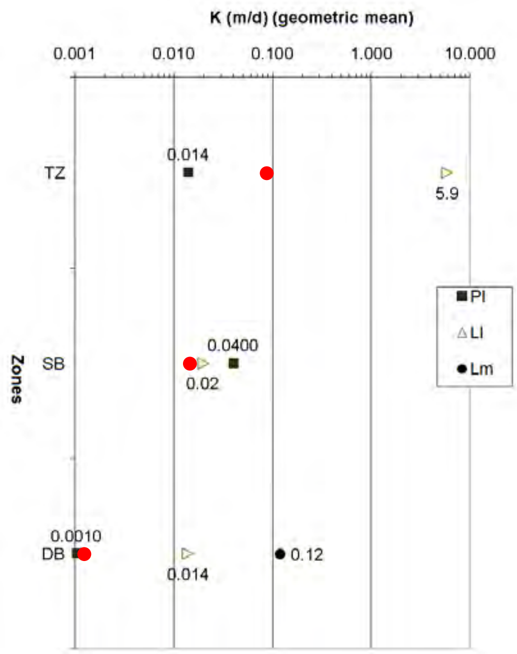


Figure 7. Variation of permeability with groundwater flow zone (Transition, Shallow and Deep) in fractured bedrock with Lm, Ll and Pl aquifer categories. (Adapted from Kelly *et al.*, 2015).

Red dots show average permeability per groundwater flow zone from Comte *et al.* (2012).

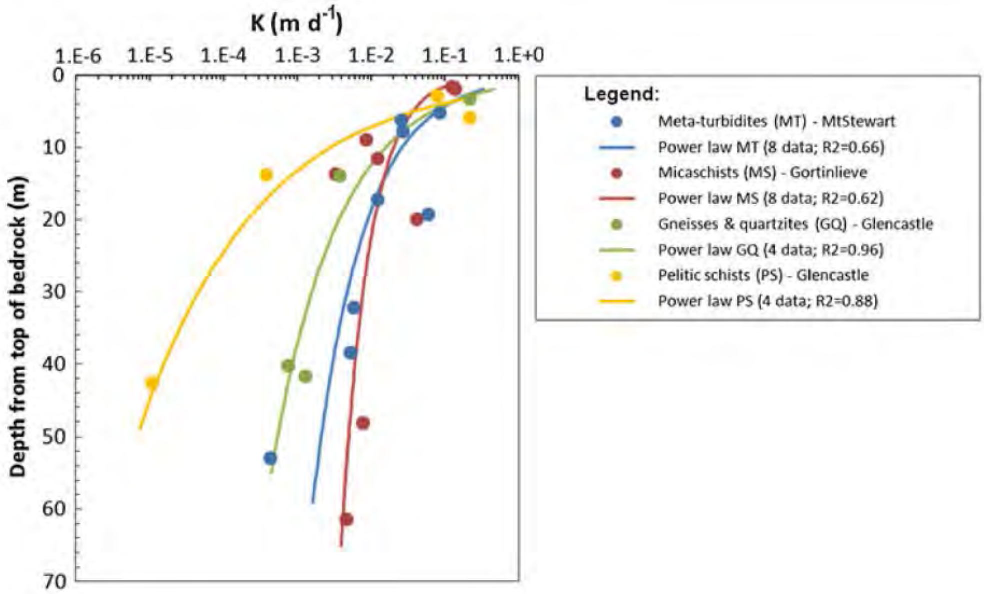


Figure 8. Decrease of permeability with depth in three poorly productive fractured bedrock aquifers. From Comte *et al*. (2012). © Springer Nature. Reproduced with permission. Licence number 4566570866570.

4. IMPLICATIONS FOR YIELD SUSTAINABILITY

4.1 DECREASE IN YIELD DUE TO DEWATERING OF PERMEABLE ZONES

The generally highest bulk permeability zone within poorly productive fissured aquifers, the Transition Zone, is frequently unsaturated. Even when saturated, once a borehole is pumped and a cone of depression develops around the well, it will nearly always become dewatered, after which it no longer contributes in terms of groundwater flow pathways to the borehole. As the cone of depression evolves, the water level in the pumping well decreases. Depending on the depth to which interconnected fracturing is developed within the aquifer, the transmissivity of the fracture network and its connectivity, and the pumping rate, this 'shallow bedrock' (**Figures 1 and 7**) or 'zone of more interconnected fracturing' (**Figure 2**) may also be locally dewatered. At this point, groundwater levels in the pumping well can decrease rapidly, generally followed by a reduction in yield.

Figure 9 shows an example of pumping water level drop off in a new public water supply borehole that was being test pumped. The bedrock in the vicinity of the borehole is fissured impure and pure limestone, and the aquifer classification is Ll – Locally important aquifer that is productive only in local zones (Kelly, 2004). There is a major northeast–southwest fault zone around 140 m to the west. The driller noted that the main inflow was from a fracture zone at >45 m, so this setting represents initial dewatering of more fractured shallow bedrock and then the 'deep groundwater and zone of isolated fractures'. It is a useful illustration of highly non-linear groundwater level variation due to variation in permeability with depth in the aquifer.

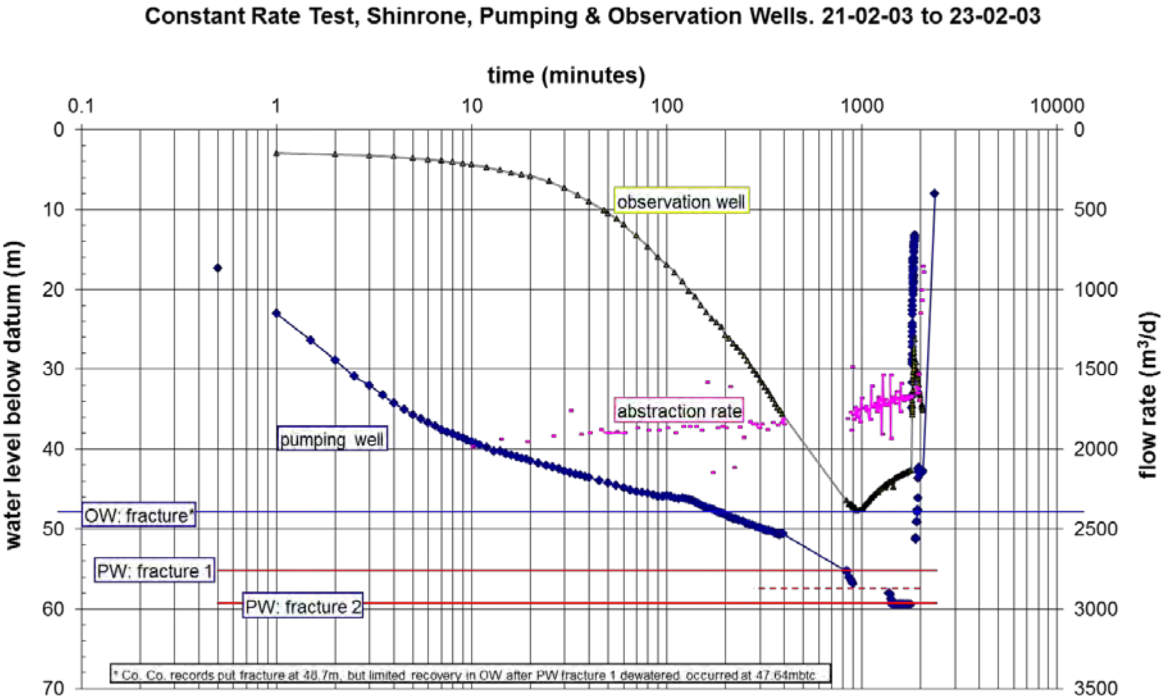


Figure 9. Decrease in water level in pumping well due to fracture dewatering (note partial recovery in observation well at almost 1000 minutes). Data from pumping test included in Kelly (2004).

This phenomenon may occur during typical summers, with the water supply borehole regularly struggling to meet demand each summer. Or, it may only occur in years when the water table in the surrounding area is lower than usual, resulting in less 'headroom' to accommodate the additional water level change associated with pumping.

4.2 AQUIFER STORAGE AND SEASONAL CHANGES IN WATER LEVEL

In nearly all Irish fissured bedrock aquifers, storage is low (**Figure 5** and **Table 1**). At some water supply sources it has been observed that some additional storage (and transmissivity) has been provided by overlying sand and gravel subsoils. (The Transition Zone can sometimes function in a similar way, although storage is typically much lower than sands and gravels.) Whilst these deposits are not sufficiently thick or extensive to be categorised as an aquifer in their own right, they contribute flow and storage to the groundwater flow system that the borehole is tapping into. In these settings, the groundwater system is buffered, and groundwater level changes due to pumping and seasonal variations are less than they would otherwise be. However, once the coarse-grained layer is substantially dewatered due to pumping or seasonal water level falls, groundwater levels fall off rapidly thereafter.

In Irish fissured rock aquifers in typical settings (overlain by low or medium permeability glacial tills or a thin layer of soil), groundwater levels are not buffered. Once groundwater

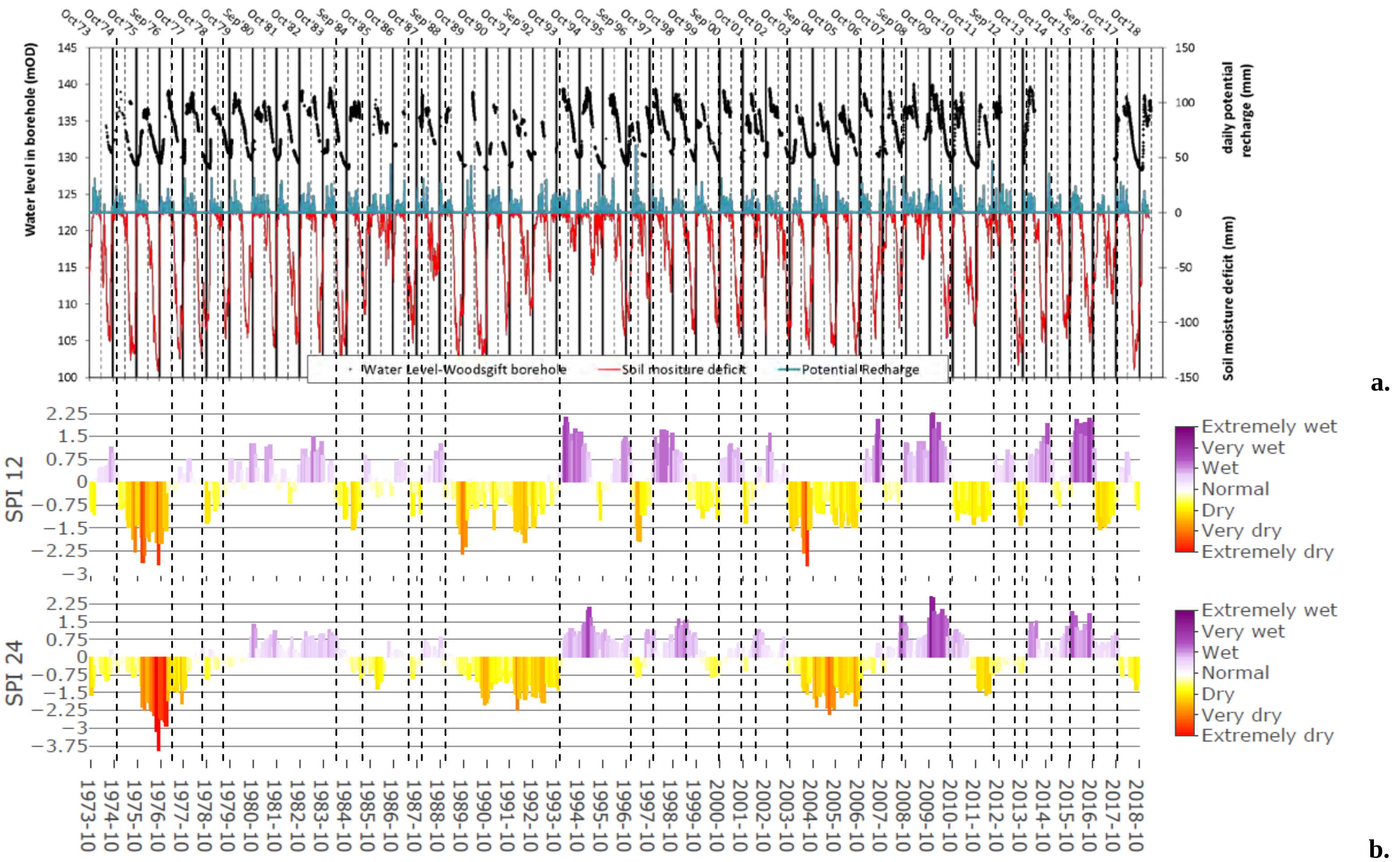


Figure 10.a (top) the variation in groundwater level, calculated effective recharge and calculated soil moisture deficit at Woodsgift Borehole, Co. Kilkenny (also known as Borrismore Creek).

Figure 10.b (bottom) Standard Precipitation Index (SPI) for 12 and 24 month windows (from Global Drought Observatory - JRC European Commission)

recharge ceases, groundwater levels fall. Seasonal groundwater level variations are on the order of 5-10 m in most (non-karst) fissured bedrock aquifers. In recharge areas, variation can be greater, and in groundwater discharge areas, seasonal groundwater level variations can be a metre or two (Tedd *et al.*, 2012). Seasonal groundwater level variations in karstic aquifers can be greater than 15 m due to their extremely high transmissivity and low storage (GSI, in prep.), whereas in sand and gravel aquifers, seasonal variations are typically on the order of 1 – 1.5 m.

Figure 10 shows the seasonal variation in groundwater level over time at an unpumped borehole in Kilkenny. This is the borehole with the longest semi-continuous groundwater level record in Ireland. Measurements were started by GSI, maintained with OPW's support, and the borehole is now part of the EPA's groundwater level monitoring network. The borehole is 33.2 m deep and is located in diffusely karstified Ballyadams Formation limestone in a low-lying, generally flat setting. It is covered with 2.1 m gravel and is unconfined all year. It is noted as having a 'poor' yield. Land use in the area is tillage & grassland. Also shown is the Standardised Precipitation Index (SPI) for the same period. Two assessment lengths are shown – 12 months and 24 months. **Figure 11.a** shows that the annual groundwater level variation in the borehole ranges between approximately 128 mAOD and 140 mAOD over the duration of the 45 year long record. The minimum annual water level tends to fluctuate between 128.4 and 130.7 mAOD[3].

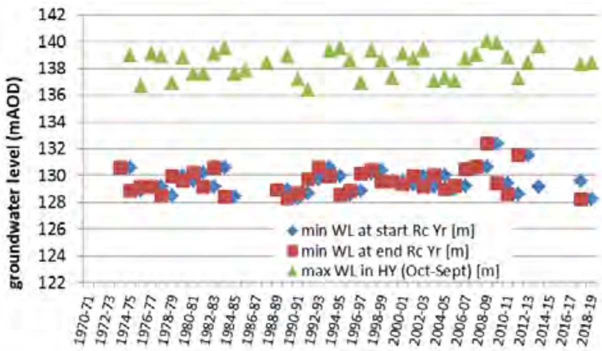


Figure 11.a. Maximum and minimum groundwater levels within a hydrological year at Woodsgift/ Borrismore Creek

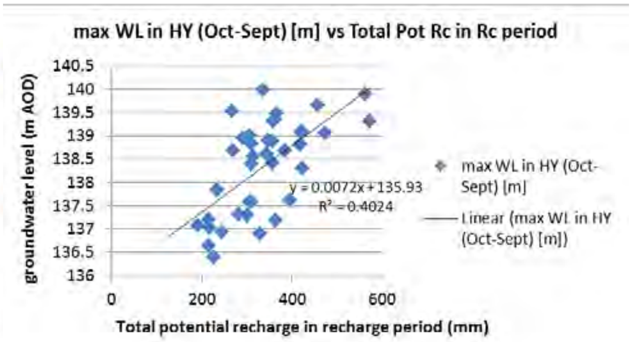


Figure 11.b. Maximum groundwater level (m) within a hydrological year at Woodsgift/ Borrismore Creek vs. estimated total potential recharge (mm)

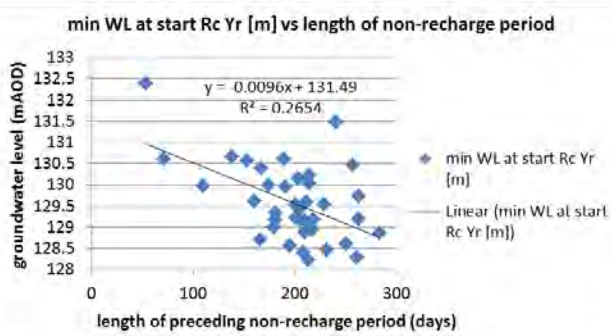


Figure 11.c. Minimum groundwater level in the at Woodsgift/ Borrismore Creek borehole at the start of the recharge period vs. the length of the non-potential recharge period

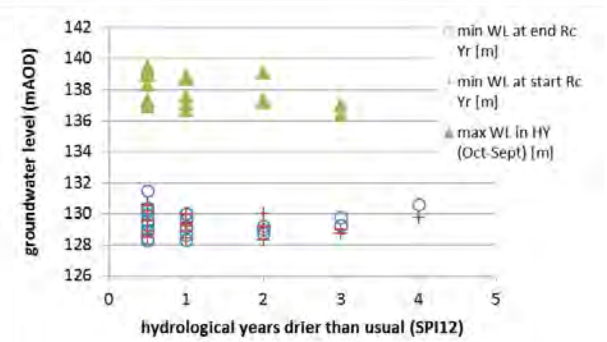


Figure 11.d. Minimum & maximum groundwater level at Woodsgift/ Borrismore Creek borehole vs. the length of the drier than usual period derived from Figure 10.b (SPI12)

Figure 11.b shows that there is a relatively good correlation between the maximum groundwater level recorded within a hydrological year and the total potential recharge that year. There was *no* correlation at at all (R^2 0.00004) between minimum groundwater level and potential recharge in the

[3] The lowest water level recorded (128.231 mAOD) was last summer, which was 5 cm lower than the next lowest record in 1990. The drought of 1976 is 12th in rank.

preceding recharge. However, there is a moderate correlation between the length of the non-recharge period and the lowest groundwater level (**Figure 11.c**).

Figure 11.d shows an analysis of the minimum groundwater level within a hydrological year as a function of the length of the drier-than-usual period as determined from the SPI12 graph (**Figure 10.b**) indicates that there is a multi-year impact on minimum groundwater level. However, this is not a large impact, and mainly results in less variability. There seems to be less influence on maximum groundwater levels of multi-annual dry spells. The quick recovery of groundwater levels post drought years (e.g. 1976, 1994, 2018), and overall stability of the seasonal groundwater variation range over the >40 year record, seems to indicate that the low storage aquifer at Woodsgift/Borrismore Creek is resilient in the face of historical weather patterns.

5. SUMMARY

Developing sustainable yields from Irish bedrock aquifers requires an understanding of the nature and distribution of the fissuring that generates permeability within the aquifer, and how this will influence groundwater supply source development and operation. In order to access the generally highest bulk permeability horizons within poorly productive aquifers, maintaining a relatively low drawdown over a steady pumping profile will work best, and give the best chance of achieving a year-round sustainable yield. This may necessitate drilling more than one borehole to meet demand.

The low storage capacity of Irish fractured bedrock aquifers in one sense is a drawback: low storage results in seasonal groundwater level declines of at least several metres, and often more. This results in a decrease in saturated thickness of the typically most transmissive parts of the aquifer (the ‘shallow bedrock’/’zone of more interconnected fissuring’), which then impacts on possible abstraction rates. However, low storage may also be seen as beneficial, since groundwater levels recover rapidly with the onset of the groundwater recharge period.

6. OUTSTANDING ISSUES AND FURTHER WORK

The assessment of the groundwater level data only describes one borehole in one aquifer type. Other aquifers are may behave differently, and may not exhibit similar apparent overall resilience to dry weather conditions. Furthermore, only historical records have been analysed. To understand better well field behaviour, and the potential impacts of predicted climate change, forward modelling should be undertaken. Assessment of additional records will be undertaken over the coming months within the GeoERA project, TACTIC. Elia Cantona at TCD is currently approaching forward modelling under different climate change scenarios.

Whilst the Aquifer Parameters Database (Kelly *et al.,* 2015) is a very useful resource, there are many more data that should be included to help make the database and statistics more robust. Input from the hydrogeological community would be very welcome. The EPA’s groundwater level monitoring network and online database (hydronet) will allow derivation of Sy from additional hydrographs.

Operational pumping data (SCADA) are of significant value in assessing the behaviour of the local groundwater system under pumping conditions, and the ability of the aquifer and borehole to give a sustainable yield under seasonal and varying climatic conditions. These data are typically not used beyond operational settings and are often not readily accessible, but should be seen as an important resource for characterising a groundwater system and its response to recharge and pumping.

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THE VULNERABILITY OF PEATLAND ECOSYSTEMS TO A CHANGING CLIMATE AND INCREASES IN THE FREQUENCY AND SEVERITY OF DROUGHTS

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ABSTRACT

Peatlands are vast carbon reservoirs, having accumulated decayed vegetation over millennia, and continue to actively sequester carbon dioxide (CO_2) where ecohydrological conditions maintain water saturation and anoxia. However, land management practice in Ireland has rendered only a small proportion of a once expansive area of peatland suitable for conservation and in an active peat-forming condition. Hydrological management is thereby implemented to arrest degradation and restore their ecological functioning. However, such conservation effects may be undermined by climate change. Projected increases in temperature will potentially increase the rate of biomass decay, with implications for atmospheric CO_2 emission and dissolved organic carbon (DOC) leaching to fluvial watercourses. Whilst climate change may negate the impacts of restoration activities implemented to address land management pressures, land management decisions that protect peatlands from further damage will increase ecosystem resilience and help slow climate change and mitigate the impacts. Peatland restoration and protection should therefore form an integral part of a national climate adaptation and mitigation strategy. However, further research is required to examine how expected increases in mean annual temperature and precipitation could alter the critical environmental variables in Irish ombrotrophic peatlands and their vegetation successions. This is particularly the case of cutover and mined peatlands, which are already unstable systems with large CO_2 and DOC emissions.

Introduction

Peatlands cover just 3% of the world's land surface, yet are the earth's most important terrestrial carbon (C) store. They annually sequester 0.37 gigatonnes of CO_2 a year (Yu et al., 2010) and have accumulated as much as 600 gigatonnes of C (GtC) since the Last Glacial Maximum (Frolking *et al*., 2010). This is twice as much C as is stored in the Earth's forests combined (Ise et al., 2008) and greater than the cumulative 535 GtC emitted to the world's atmosphere at the end of 2013 (IPCC, 2014). The peatlands' capacity to sequester and store significant volumes of C is a function of their ecosystems' unique ecohydrology. The environmental conditions created by this ecohydrology drive a biomass decomposition rate that exceeds the ecosystems net primary production (NEP) – i.e., while the amount of organic C produced by peatland vegetation by photosynthesis is low compared to a tropical rainforest for example, the biomass that is generated does not readily break down due to a prevalence of saturated conditions limiting decay. Biomass thereby accumulates as peat substrate and is a process that is regulated, and limited, by water supply and oxygenation. Peatlands are thus low-energy ecosystems that require physiographic and climatic conditions that favour water retention and peat accumulation (Roulet, 2000; Fraser et al., 2001; Price, 2003). However, exploitation has damaged their ecohydrological functioning and greatly diminished their global distribution, particularly in Western Europe where peatlands are now priority habitats for protection. Alterations in hydrology has thereby transformed peatlands from long-term C sinks into sources (Joosten, 2009; Young et al., 2017; Leifeld and Menichetti. 2018), and hydrological management is required to restore the plant communities that give rise to the C sink function. However, such management is now complicated by climate change and alterations in the global water cycle. Whilst peatland ecosystems are typically resilient to periodic changes in climate, this is not the case for degraded systems. This paper examines the potential vulnerability of Irish peatlands to climate change, the impacts on greenhouse gas emissions (GHGs) and the implications for ecological restoration.

Peat accumulation and carbon cycling

Peatlands, as they are found today, began their development in the Holocene (ca. 11,700 ya to present). It is estimated that the rate of C accumulation over the last 6,000 – 8,000 years is between 20 and 30 g C m^{-2} yr^{-1} (Gorham, 1991; Roulet et al., 2007), demonstrating a slow, but persistent, C uptake over several millennia (Roulet et al., 2007). Contemporary carbon balance studies, which measure the exchange of CO_2 with the atmosphere (the NEP), and the loss of C as methane (CH_4) and dissolved organic carbon (DOC), finds considerable inter-annual variability in the peatland carbon balance, with losses substantial in winter months (Roulet et al., 2007). In degraded systems, peatlands are persistent C sources (e.g. Billet et al, 2004; Rowson et al., 2010), and also C sinks in intact systems (e.g. Roulet et al., 2007; Nilsson et al., 2008); yet intact systems can also become net sources following drought or below-average dry years (e.g. Alm et al, 1999; Arneth et al, 2002; Roulet et al., 2007; Koehler et al., 2011). However, despite being significant sources of atmospheric CH_4 and exporters of DOC to the oceans (Belyea and Baird, 2006), and the high variability in inter-annual net ecosystem exchange (NEE) peatlands are, over extended time-periods, consistent C sinks (Lund et al, 2010).

Peatland in Ireland

Peatland habitats in Ireland cover up to 21% of the landscape and occur across a distinct biogeographical climatic gradient, spanning upland and low-lying ombrotrophic (rain-fed) bogs to groundwater-fed fens. Ombrotrophic peatlands, comprising raised and blanket bogs, constitute the vast majority of this peatland area (ca. 93%), and while both fens and bogs appear in natural condition, the majority have been modified by man (NPWS, 2015). Of the peatland area remaining in Ireland, only ca. 17% is considered to be in its 'natural' form, with cutover bog from domestic peat cutting (17%), afforested bog (39%), bog converted to agricultural grassland (19%), production bog for energy consumption and horticulture (4%) and rehabilitated bog (1%) comprises the remaining peatland area (NPWS, 2015).However, of the remaining natural bog, only ca. 60% is considered worthy of conservational value and protected as European Sites under the Habitats Directive (Council Directive 92/43/EEC). Moreover, considerably less than this is considered as 'active' bog with peat-forming vegetation (sequestering C), with less than 6% of the protected raised bog network mapped as active raised bog. It is not known how much of the blanket bog (comprising two-thirds of all peatland) are peat-forming, but it is likely to be around 30%.

Thus, peatland is a significant source of C in Ireland due to a long history of unsustainable management through drainage, land conversion to forestry and agriculture and commercial and domestic peat extraction. Current estimates are that peatlands are a source of 2.64 Mt C per year (equivalent to 9.66 Mt CO_2) (Renou-Wilson et al., 2011); however, much uncertainty remains as to their true C emissions, and will be continually informed by advances via research projects such as SmartBog (http://smartbog.com/) and as part of the Environmental Protection Agency (EPA) reporting on greenhouse gas emissions and removals from land use, land use change and forestry (LULUCF) to the European Union (EU) 2030 Climate and Energy Framework.

Ecohydrology and drainage

Ombrotrophic peatland ecology is dominated by bryophytes from the genus *Sphagnum* (Robroek et al., 2009), whose stability is dependent on the dynamics of the water table relative to the ground level (Regan et al., 2019a). Persistently high water tables (< 0.15 m depth) are maintained where climatic, geomorphological and hydrogeological conditions are suitable. The bulk of a bog system consists of peat as a low permeability medium (catotelm), which rests on or in a regional groundwater body that may have a variable hydraulic connection with the wetland above. In contrast, the near-surface (< 50 cm) consists of a layer of growing vegetation (acrotelm), dominated by *Sphagnum* spp. mosses, which is considered an 'active' layer with storage properties that respond much differently to rainfall than the peat beneath (Regan et al., 2019b). Whilst the bulk of the runoff and water storage processes occur primarily in the acrotelm, as the porous structure of the *Sphagnum* provides a permeable layer for water transmission, these processes are strongly controlled by the hydrogeological properties of the peat (Regan et al., 2019a).

When drained, peat deforms due to consolidation and organic matter oxidation and releases stored C to the atmosphere. The alteration of the peat's hydraulic properties means water is not retained on the bog surface, and the acrotelm, which supports the *Sphagnum*, degrades and the bog no longer accumulates peat. Thus, peatland C and water cycling are tightly coupled (Frolking et al., 2010). Whilst the water table is the primary factor driving C dynamics, temperature is also an important environmental control, particularly with regards to CH_4, which is generated by bacteria in anaerobic conditions, but increases with increased soil temperature. The release of CH_4 also increases where vascular plants (e.g., *Eriophorum*)) are present, due to the porous structure of their roots (*Sphagnum* moss has no roots). Similarly, DOC emissions from peatlands are also partially biogeochemically controlled, and increase with increasing temperature (Koehler et al., 2009; Regan et al., 2019b).

Climate change
Climate controls the hydrological baseline conditions that allow peat formation and ecosystem stability in undisturbed settings. The water table is the primary determinant of soil-organic-carbon dynamics, meaning changes in climate will also drive ecological change. Sustained periods of water deficit lead to drought conditions that reduce bog runoff and lower water levels. Peatland vegetation emits CO_2 during respiration, which increases with rising temperature. Increases in atmospheric CO_2 and temperature can potentially increase the growing season of vegetation, and thereby their productivity and carbon assimilation capacity. However, such a positive feedback process is compromised by persistently lowered water tables, which increase CO_2 emissions due to the decomposition of the surface vegetative layer and shallow peat. Similarly, warmer temperatures increase the rates of microbial decomposition and cause an increase in DOC in water released from the peatland. The predicted changes in precipitation and temperature regimes due to climate change will therefore lead to enhanced water losses.

Current global warming projections for Ireland in the period 2041-2060 (Nolan *et al*., 2017), using a high emissions scenario, predict significant decreases in mean annual, spring and summer precipitation amounts. Reductions are predicted to be greatest during summer months (>20%), with the number of extended dry periods also projected to increase substantially by mid-century during autumn and summer. Whilst it is unknown how resilient peatlands are to an increase in the frequency and severity of droughts, it is expected that the ecological consequences will be largely negative. Climate change will therefore impact on the peatland carbon sequestration function, result in the destabilisation of stored C and increase nutrient and DOC emissions, thus degrading freshwater quality.

Vulnerability and resilience
Peatland ecosystems are generally considered to be resilient to fluctuations in climate (e.g., Gallego-Sala et al., 2018); though most models predict global peatland decay with temperatures > 4° higher than present. However, ecosystems are resilient only when their structure is left intact, such as the great peatland expanses found in Canada and Russia. This is not the case for the majority of peatlands in Ireland, which have been fragmented, and drainage pressures have altered their hydrogeological properties and their water retention capacity. Moreover, wetlands that are primarily dependent on precipitation for their water supply are highly vulnerable to climate change, whilst those dependent primarily on discharge from regional groundwater flow systems are the least vulnerable, because of the great buffering capacity of large groundwater flow systems to climate change (Winter, 2000).

The current projections for Ireland (Nolan et al., 2017) imply significant increases in the frequency and severity of droughts, indicating that peatlands in Ireland are highly vulnerable to climate-induced hydrological change, with increased evapotranspiration rates and lower rainfall during the critical growing period. This will affect ecosystem stability and increase nutrient and greenhouse gas (GHG) emissions, whilst negating the impacts of restoration activities implemented to address land management pressures. Whilst the adaptation ability of peatland ecosystems to these climatic variabilities will depend on the rate and extent of global warming, land management decisions that protect peatlands from further damage will increase ecosystem resilience and help slow climate change and mitigate the impacts. Peatland restoration and protection should therefore form an integral part of a national climate adaptation and mitigation strategy.

Thus, whilst peatlands are considered to be resilient systems to gradual changes in climate, ecosystem stability is lost when critical environmental thresholds are passed. In ombrotrophic systems, the stability of the acrotelm and the water table dynamic is the critical driver of GHG emission (Regan et al., 2019). However, the depth to which *Sphagnum* can efficiently access water via capillary action in this zone is relatively shallow, < 0.2m from the ground surface. The resilience of *Sphagnum* spp in areas of remaining near-intact peatland in Ireland to prolonged and frequent water table drawdown due to rising air temperatures and decreased annual rainfall is unknown, but likely to be negative. There is already international evidence that climate change is driving increased DOC losses from peatlands. Freeman et al. (2001a) and Worral et al. (2006) postulate that rising temperatures are driving an increase in DOC concentration in freshwaters from peatlands across the UK. The mechanism behind this is drought augmenting DOC production by causing a drop in water table below the long-term acrotelm-catotelm boundary, triggering enzyme-latch mechanisms (Freeman et al., 2001b). Whilst droughts occur naturally, more severe and frequent- droughts likely trigger a longer term biogeochemical response (Worral et al., 2006), which is further attenuated by land management practice.

Conclusions

The unsustainable management of peatland ecosystems significantly alters their hydrological and ecological characteristics. This has negative implications for biodiversity and climate mitigation, whilst also increasing their vulnerability to future climatic variation in temperature increases and rainfall distribution. It is critical that land management practice does not further disrupt the peatland carbon store. Whilst the recovery of carbon sequestration potential in Irish peatlands is limited due to irrecoverable changes in hydrogeology, the carbon stored as peat in the ground is a potential significant carbon source. Peatland restoration and conservation can thereby serve as an important land-based mitigation management strategy to limit the persistent release of carbon dioxide from drained peatlands through oxidation and is a climate change action that can contribute to the reduction of atmospheric greenhouse gases. The most recent IPCC report (IPCC, 2018), states no more than 465 GtC can be emitted to the earth's atmosphere to keep global temperatures below 2°C above pre-industrial levels, meaning countries with a large proportion of land cover mapped as peat soil, such as Ireland, must ensure that land-use does not further exacerbate the pressures already faced in attaining sustainable energy production/consumption, transport and agriculture. However, considering the poor historical management of peatland in Ireland, and the challenges faced in the eco-hydrological restoration and rehabilitation of degraded systems, these peatlands are acutely vulnerable to the projected climate changes and are not resilient like the large expanses found in regions such as Canada and Russia. It is therefore critical that guidelines for the ecological management of peatlands now incorporate the predicted changes in the hydrological cycle incurred by climate change and are developed accordingly.

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WORKSHOP

AN INTERACTIVE WORKSHOP OUTLINING THE USE AND BENEFITS OF OPEN-SOURCE QGIS FOR HYDROGEOLOGISTS

Shane Carey

Geological Survey Ireland

NOTES

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