01 – REMOTE SENSING FOR GROUNDWATER FLOOD MAPPING, MONITORING, AND SHORT- AND LONG-TERM FORECASTING

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Abstract

Karst related groundwater flooding is a significant hazard in many rural communities in Ireland. In response to the unprecedented flooding events of winter 2015-2016 Geological Survey Ireland started a collaborative project (GWFlood, 2016-2019) to investigate the drivers, map and numerically model the extent of karst groundwater flooding in Ireland, with particular emphasis on seasonal karst lakes known as turloughs. The practical limitations of in-situ monitoring of over 400 turloughs supported the use of remote sensing and GIS techniques to delineate flood extents and monitor flood prone areas using satellite imagery such as of the ESA Copernicus programme. With limited recorded groundwater flood data in Ireland, the use of remote sensing data provides historical archives of images to look at past flood conditions to optimise the detection of groundwater floods and delineate maximum groundwater flood extent maps. These new data improved the fundamental hydrological understanding of groundwater flooding in Ireland, enabling key stakeholders to develop appropriate flood mitigation measures and allow for informed flood assessments to be made in future. Following on from this work, Geological Survey Ireland has started a new collaborative project (GWClimate, 2020-2022) that uses satellite derived hydrological data to quantify the impact of climate change on Irish groundwater resources, and to provide relevant data for reducing the impact of forthcoming floods and droughts.

1. INTRODUCTION

Groundwater flooding low lying in karst areas affects many rural communities in Ireland, with floods extending up to hundreds of hectares during the winter flood season, lasting for weeks or even months. Ireland's karst groundwater floods are mainly related to the limestone areas of the western lowlands, with flow systems fundamentally linked to bedrock geology and characterized by high spatial heterogeneity, low storage, high diffusivity, and extensive interactions between groundwater and surface water, which leaves them susceptible to groundwater flooding (Naughton et al., 2017). During intense or prolonged rainfall periods the solutionally-enlarged flow paths are unable to drain recharge and available sub-surface storage rapidly exceeds its capacity. Consequently, surface flooding occurs in low-lying topographic depressions known as turloughs, which represent the principal form of extensive and recurrent groundwater flooding in Ireland (Mott MacDonald, 2010; Naughton et al., 2012). There are over 400 recorded turloughs across the country, with the majority located in the limestone lowlands in counties Roscommon, Galway, Mayo and Clare (Figure 1).

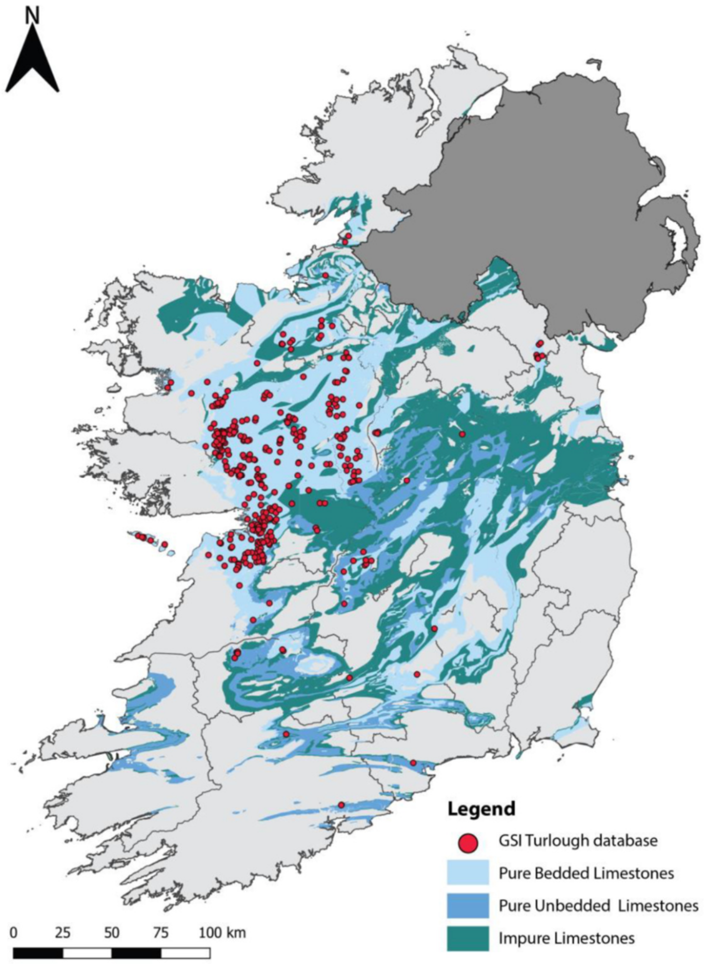

Figure 1: *Locations of limestone and turloughs in Ireland (limestone layers derived from GSI Hydrostratigraphic Rock Unit Groups map).*

In response to the serious flooding of winter 2015/2016 specifically related to turloughs, the Programme for a Partnership Government (2016) stated that resources would be provided for *"studies into individual problematic (prone to flooding) Turlough systems, if requested by a local authority or another relevant State agency"*. Geological Survey Ireland (GSI), a division of the Department of Communications, Climate Action and Environment (DCCAE), and the leading national authority on groundwater science, delivered on this commitment by initiating a new three-year project (GWFlood), in collaboration with Trinity College Dublin (TCD) and subsequently the Institute of Technology Carlow (ITC), to investigate the drivers and extent of karst groundwater flooding in Ireland. Through the GWFlood project a flood mapping procedure was developed and implemented to delineate flood extents and monitor flood prone areas considering Sentinel-1 satellite imagery, hydrological models, and long-term meteorological data. The combination of these datasets within geographic information systems (GIS) were used to deliver: 1) a national historic groundwater flood map, 2) predictive groundwater flood maps of 10%, 1% and 0.1% annual exceedance probabilities (AEPs), and 3) a methodology for hydrograph generation using satellite images.

Following on from this work, GSI has started a new project (GWClimate, 2020-2022), in collaboration with ITC. The goal of this project is to evaluate the influence that climate change may have on Irish groundwater resources, both in terms of groundwater flooding and drought issues, and provide tools to assist communities and local authorities to react to impending flood risks. Central to this work there is the monitoring of groundwater floods using remote sensing to enable short- and long-term forecasting of groundwater floods at a national scale.

2. GWFLOOD PROJECT (2016-2019)

The methodology developed under the GWFlood project for flood mapping using satellite images primarily considered: 1) Ground-based monitoring stations measuring groundwater levels at sites of interest that were used to calibrate and validate the results from satellite images, 2) synthetic aperture radar (SAR) satellite images from Sentinel-1 used to map flooded areas and generate the associated hydrographs, and 3) hydrological numerical models used to reproduce rainfall and groundwater level time series that allowed us to estimate the annual exceedance probabilities at over 300 sites in Ireland.

2.1 Monitoring Stations

During winter 2016/2017 over 60 exploratory monitoring stations were installed in turloughs and lakes across counties Galway, Clare, Mayo, Roscommon, Longford and Westmeath measuring stage and temperature using Solinst Leveloggers®. The data from these sites improved the understanding of the hydrodynamics and flooding potential of turlough systems across key catchments and provided model calibration and validation data. Exploratory data were also used to inform the site selection process for the permanent monitoring network.

The installation of permanent monitoring stations began in summer 2017 and was completed in mid-2019. A subset of 18 sites representative of the spectrum of groundwater flooding conditions were established as permanent telemetered stations providing real-time information on water levels. Data from these stations 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, and the modem transmits data recurrently via SMS to an online web portal. Data from the telemetry network is accessible to the public through our Groundwater Level Data Viewer https://gwlevel.ie/ (Figure 2).

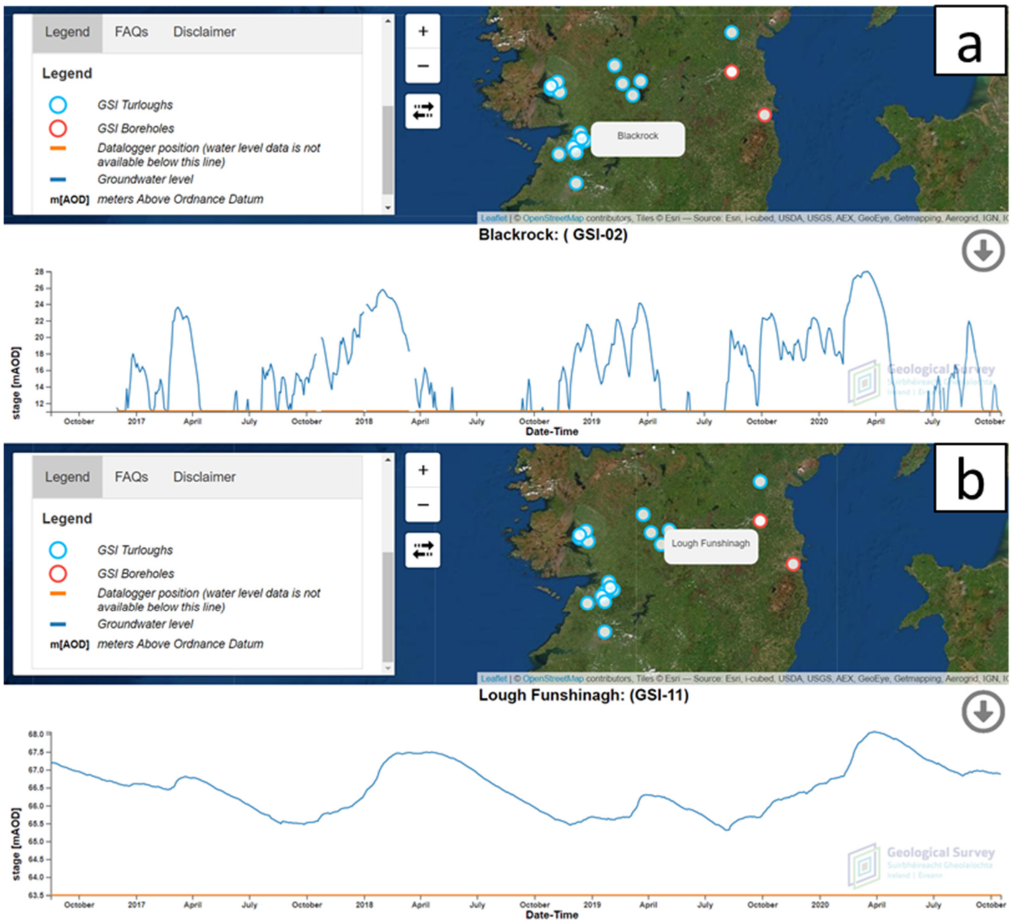

Figure 2*: Two examples of groundwater level data from the permanent monitoring network for groundwater floods. a) Blackrock, b) Lough Funshinagh.*

2.2 Satellite Flood Mapping

Effective flood risk management requires the ability to describe and map how groundwater floods develop and recede at a national scale in time and space. While traditional monitoring is an effective tool at priority sites, the distributed nature of groundwater flooding in karst lowlands hampers any systematic monitoring efforts. Floods tend to occur in isolated basins across the landscape and so would require an impractical amount of field monitoring to provide a complete picture.

Remote Sensing (RS) and GIS approaches offer significant advantages in this respect. Passive satellite imagery, such as the USGS Landsat or ESA Copernicus Sentinel-2 programmes, can be used to image and delineate floods at a catchment scale. In the case of Landsat, a long historical archive of images also allows the observation of past flood conditions and provides some data with which to validate hydrological models. However, an obvious limitation of satellite systems that require a clear view of the earth's surface is the issue of cloud cover. When cloud cover is extensive, as is often the case in Ireland during winter floods, no useful data can be collected. Under these conditions active systems, such as synthetic aperture radar (SAR), are extremely useful as they are not limited by cloud cover or time of the day. In this context, the GWFlood project used SAR imagery from the Copernicus Programme Sentinel-1 satellite constellation as its primary flood mapping tool.

SAR systems emit radar pulses and record the return signal at the satellite. The strength of this signal, also called backscatter, is largely dependent on surface roughness and geometry. Flat surfaces such as water operate as reflectors resulting in minimal backscatter signal returning to the satellite. By exploiting this low backscatter characteristic of water, it is possible to delineate the extent of water bodies (Figure 3). Several studies have demonstrated the efficacy of delineating water bodies using remotely-sensed SAR data (e.g. Matgen et al., 2011, Chini et al., 2017, Martinis et al., 2015, O'Hara et al., 2019). Based on these works, similar image processing techniques were trialled and developed under the GWFlood project to optimise detection of groundwater flood extents from SAR data in Ireland.

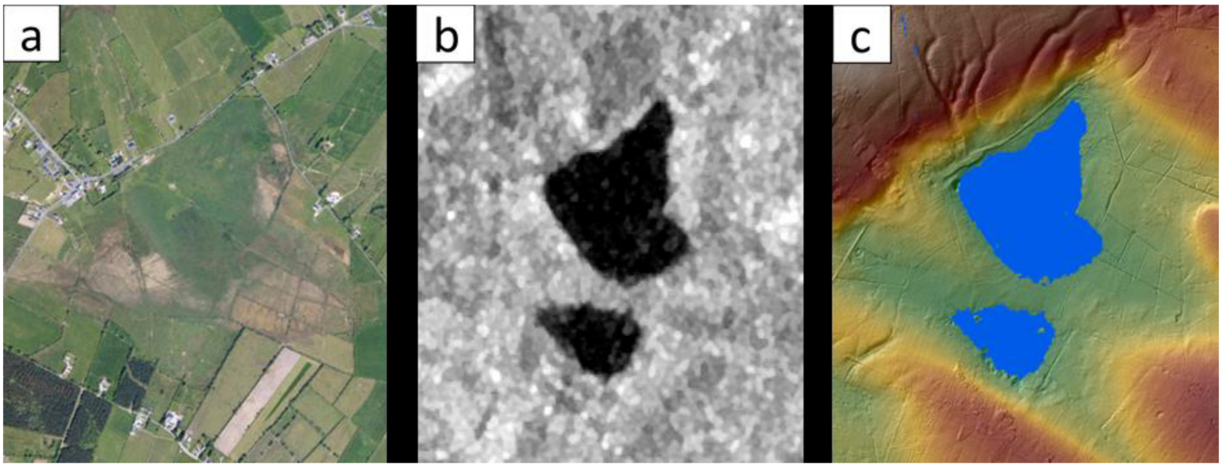

Figure 3: *Imagery of Castleplunket turlough Co. Roscommon showing: (a) orthophotography of it empty, (b) pre-processed SAR imagery of it flooded (March 2017) and (c) a SAR based water classification (blue) overlaid on LiDAR data.*

Broadly, water bodies were delineated by looking at the histogram of the SAR images and defining a threshold to differentiate between water and non-water. This approach was considered as it enabled an automated and repeatable process with minimal user interaction. The process involves the generation of a histogram of backscatter intensity values for predefined sections of the SAR image. The sections were selected focusing on regions with presence of permanent and temporary water. If the SAR image consists of both wet (i.e. low backscatter) and dry (i.e. high backscatter) pixels, the histogram should exhibit a bimodal distribution, with the peaks representing wet and dry pixels. A threshold-based approach was then applied to separate the SAR image into a binary 'wet' and 'dry' image by defining a threshold between these two peaks (Figure 4).

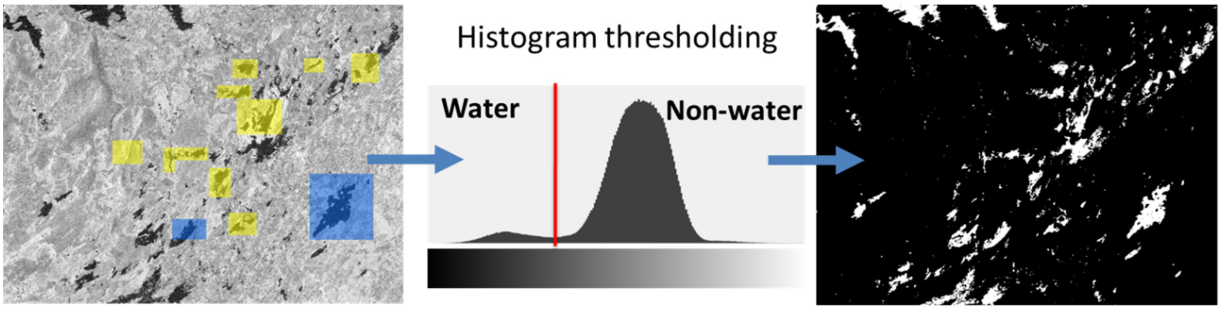

Figure 4: *Left) SAR image with high (white) and low (black) backscatter. In yellow areas used to generate the histogram associated with temporary flooded areas, in blue regions used to generate the histogram associated with permanent water bodies. Middle) bimodal histogram used to separate between water and non-water pixels. In red the threshold value used to differentiate between water and non-water pixels. Right) Mask with water (white) and non-water (black) pixels.*

Although the assumption of linking low backscatter signal to the presence of water is a well-established flood mapping technique, there are technical issues that must be addressed. For example, radar shadowing due to local topography often results in false positive pixels on leeward hillsides (i.e. the side of a slope that the side-looking Sentinel-1 sensor cannot see). In addition, not all flat surfaces necessarily indicate water. Artificially flat features such as airport runways, motorways or football pitches can produce false positives. In order to correct for these inherent technical issues, additional filtering techniques were applied when processing SAR images.

Finally, an automated process was developed to calculate the maximum extent of flood boundaries by cross-referencing the defined boundaries against topographic data to calculate the elevation of the land-water interface. This calculated flood elevation was then combined with topographic mapping to delineate a topographically corrected flood extent that enabled the mapping of floods beneath forestry, where water could not be detected from SAR images (Figure 5).

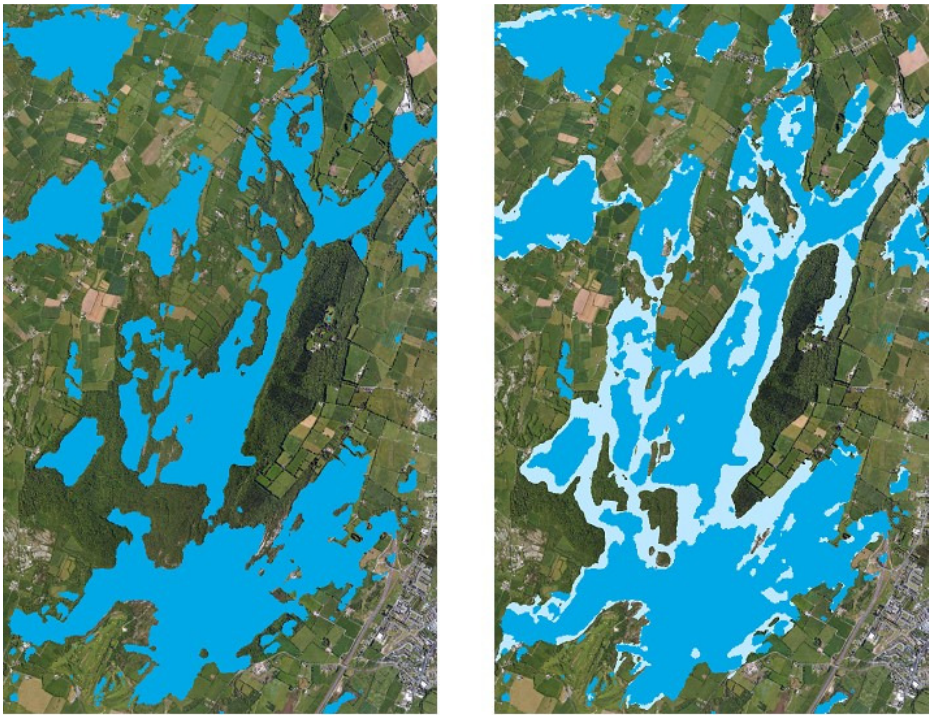

Figure 5: *Sentinel-1 derived flood extent (left) and topographically corrected flood extent (right). Background image ©DigitalGlobe, Inc.*

2.3 Hydrograph generation

SAR generated hydrographs were computed by combining satellite derived flood extents with high resolution topographic mapping, which allowed us to extract water level information from each satellite image (Figure 6). In this context, the SAR mapping methodology was adapted to reconstruct hydrometric data from as many suitable locations as possible. This approach enhances the accuracy of once-off flood extent maps as well as enabling the generation of historic flood hydrographs at an unprecedented number of turloughs in Ireland.

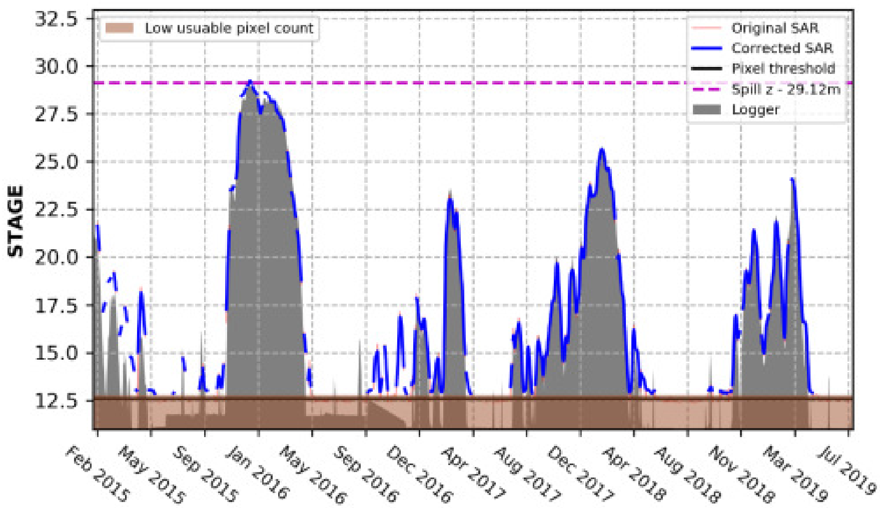

***Figure 6**: Example of a SAR-generated hydrograph (blue) compared to data from datalogger (grey) installed at Blackrock. Brown semi-transparent region at the bottom of the hydrograph shows stage values that were not considered due to low resolution. Purple dashed line indicates the spill point of Blackrock turlough.*

A first list comprising 514 turlough sites was compiled from GSI and NPWS turlough databases. Of these sites, 337 were considered appropriate for SAR analysis as their flooding was consistently large enough to be classified from SAR imagery, and there were enough pixels to accurately quantify the depth of the floods. The process of determining a site's feasibility for SAR hydrograph generation was aided by time-lapse visualisations of SAR imagery. While the purpose of these videos was to assess the feasibility of known turloughs for SAR analysis, a further benefit was the identification of an additional 149 sites which demonstrated seasonal groundwater flooding dynamics. These sites were added to the hydrograph generation inventory. A further 75 permanent water bodies (lakes, rivers or fens) were also included as they were deemed to have a seasonal groundwater flood component (e.g. the upper Fergus River). In total, 561 sites were used for hydrograph generation (Figure 7a). The resulted hydrograph agreed with the sites monitored using dataloggers, having Nash Sutcliffe (Volume) efficiencies above 0.8 for most of the sites, allowing us to reproduce stage values in Ireland for a specific day of the year, between 2015 and today (Figure 7b).

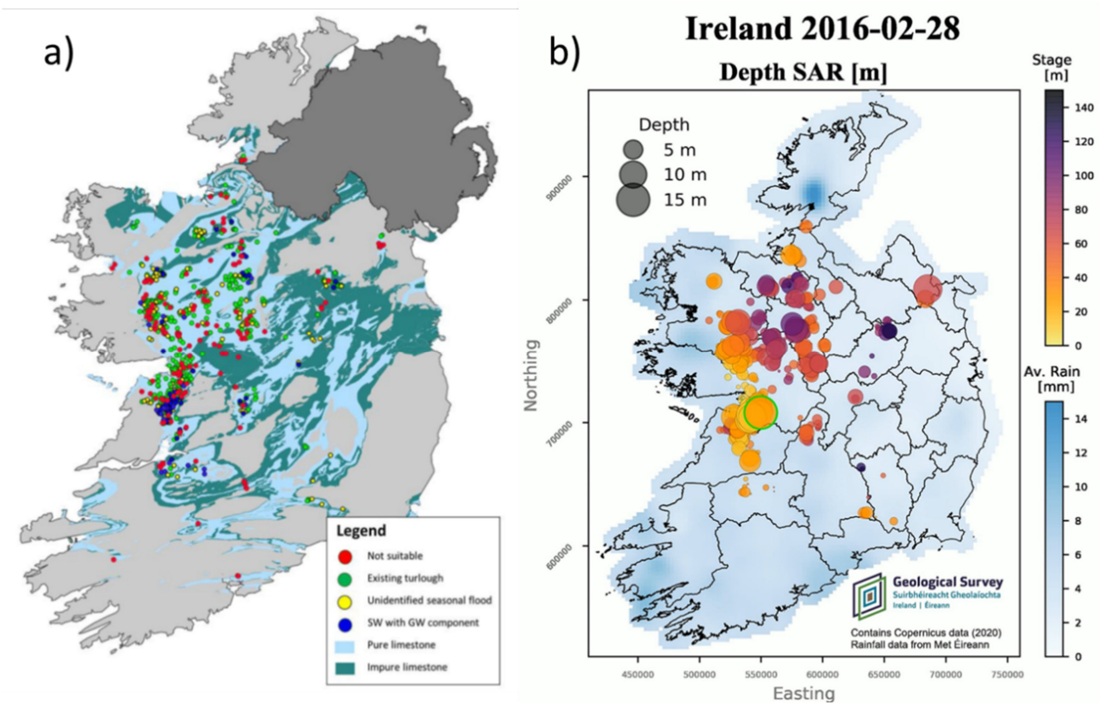

Figure 7: *a) Locations and status of groundwater flood sites used for hydrograph generation (SW: Surface water, GW: Groundwater). b) Computed stage (magma colour) and maximum flood depth (size of the circles) values at the suitable sites using SAR-generated hydrographs. Background blue colours represents the average rain over the past 20 days in [mm] calculated by interpolating data from Met Éireann stations. The green circle shows the deepest turlough for the specified day (28/02/2016), which in this case is related to Blackrock. Animation showing changes in groundwater level over time is available at the GSI youtube channel: https://www.youtube.com/watch?v=zHnxomW9VrU&t=1s*

2.4 Hydrological Modelling

Hydrological modelling was key for the generation of Predictive flood maps. Predictive flood mapping requires long-term hydrological time series to estimate future occurrence probabilities, but 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 quantify the relationship between rainfall and turlough flooding to reconstruct the requisite long-term hydrological series from observed and stochastic rainfall data.

Two fundamental approaches were considered in the GWFlood project to mathematically model groundwater floods in karst systems: distributive models and global models (Kovacs and Sauter, 2007). Distributive models use theoretical concepts such as simplified aquifer geometry and hydrodynamic flow equations to simulate the hydraulic behaviour of karst aquifers. Global models establish a relationship (transfer function) between input and output, where the input is usually a precipitation event and output the spring discharge or water level time series. 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 for most of the cases.

A generic global modelling approach was developed that could be applied to individual flood sites based on limited site-specific data such as water level, rainfall, and topography. This approach considered each site independently and did not incorporate information on the wider groundwater system. The model consider the karst aquifer as a transfer function, transforming the rainfall input signal into the output hydrograph signal, and the transfer function was taken to represent the overall (or global) hydrogeological response of the karst aquifer to recharge events (Kovacs and Sauter, 2007).

While the global modelling technique was suitable for most locations, the Gort Lowlands Catchment in Co. Galway was highlighted as a priority for distributed modelling for two reasons: 1) the catchment consists of a complex interlinking network of turloughs which are better represented by a detailed distributed model, and 2), to inform the ongoing South Galway Flood Relief Scheme by researching the effects of various engineered flood mitigation measures on local and catchment hydrology. In order to achieve this, the GWFlood project funded a 30 month TCD research fellowship to enhance a pre-existing TCD hydrological model of the Gort Lowlands (Morrissey et al., 2020).

2.5 Main Products

2.5.1 Historic Flood Maps

The historic groundwater flood map (Figure 8) is a national-scale flood map presenting the maximum historic observed extent of karst groundwater flooding. The map is primarily based on the winter 2015/2016 flood event, which in most areas represented the largest groundwater flood event on record. The map was produced based on the SAR imagery of the 2015/2016 event as well as any available supplementary evidence. The floods were classified by flood type differentiating between floods dominated by groundwater and floods with significant contribution of both, groundwater and surface water.

In addition to the historic groundwater flood map, the flood mapping methodology was also adapted to produce a surface water flood map of the 2015/2016 flood event. This flood map encompasses fluvial and pluvial flooding in non-urban areas and has been developed as a separate product (Figure 8).

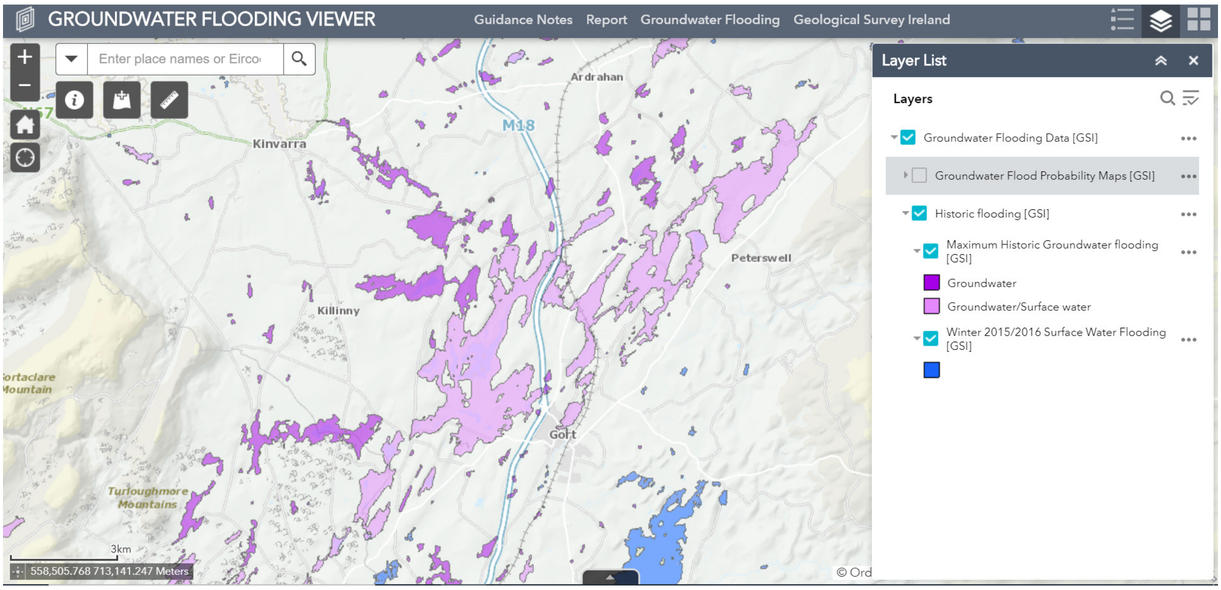

Figure 8: *Sub-section of the historic groundwater flood map and winter 2015/2016 surface water flooding available from the GSI Groundwater flooding viewer.*

2.5.2 Predictive Flood Maps

The predictive groundwater flood map (Figure 9) presents probabilistic flood extents for selected locations of recurrent karst groundwater flooding. It consists of a series of stacked polygons at each site representing the flood extent for AEPs of 10%, 1% and 0.1%. The map is focussed primarily (but not entirely) on flooding at seasonally inundated wetlands known as turloughs. Sites were chosen for inclusion in the predictive map based on existing turlough databases as well as manual interpretation of SAR imagery.

The mapping process tied together the observed and SAR-derived hydrograph data, hydrological modelling, stochastic weather generation and extreme value analysis to generate predictive groundwater flood maps for over 400 qualifying sites. It should be noted that not all turloughs are included in the predictive map as some sites could not be successfully monitored with SAR and/or modelled.

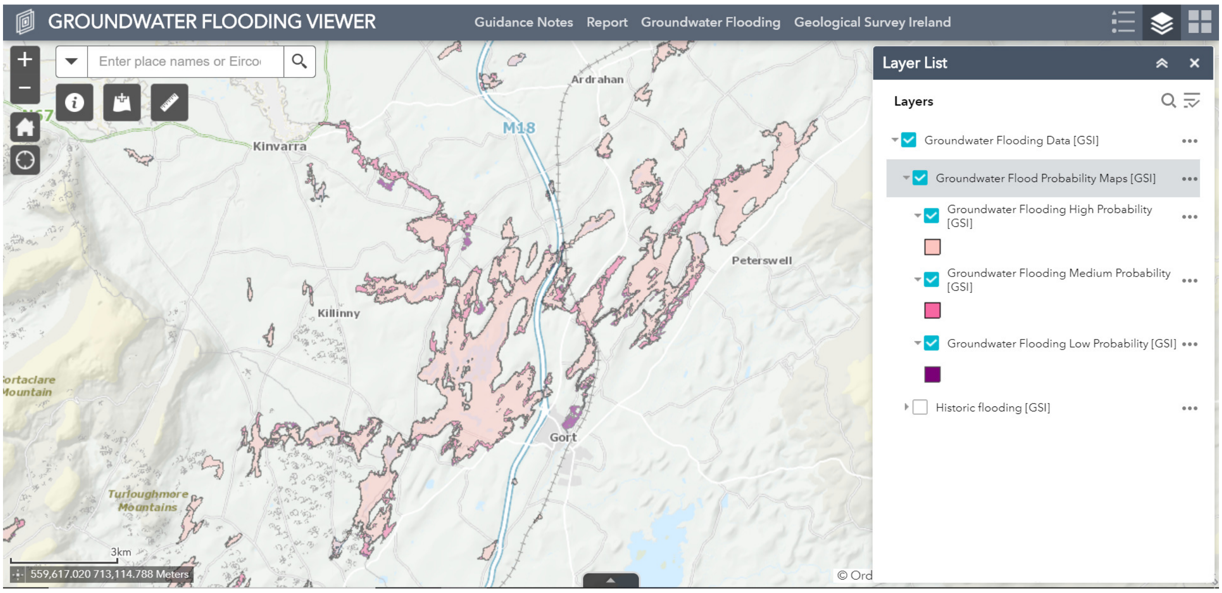

Figure 9: *Sub-section of the predictive groundwater flood map available from the GSI Groundwater flooding viewer.*

3. GWCLIMATE PROJECT (2020-2022)

It is now accepted beyond doubt that anthropogenic greenhouse gas emissions are significantly altering the Earth's climate (IPCC, 2013). More unprecedented high-impact climate extremes were recorded in the first decade of the 21st century than any previous decade (World Meteorological Association, 2013). Globally a rise in average temperature of between 0.3 and 4.8°C is projected by the late 21st century, while the Intergovernmental Panel on Climate Change (IPCC) estimates the frequency and proportion of heavy precipitation will likely increase and droughts intensify in many regions (Senevirante et al., 2017).

In an Irish context, there has been a 0.5°C increase in mean annual air temperature during the period 1981-2010 compared to 1961-1990 (Walsh, 2012). Analysis of high-resolution regional climate simulations shows this trend continuing with a projected increase in annual temperatures of 1.24°C (RCP4.5) and 1.6°C (RCP8.5) by mid-century (O'Sullivan et al., 2016). Studies also suggest that a warming climate will likely result in an increase in high-impact weather events such as prolonged dry periods, heavy rain episodes and prolonged warm spells (O'Sullivan et al., 2016, Nolan et al., 2017). Climate change will thus be a major driving force in shaping Ireland's water resources and environment in the coming decades, exacerbating existing pressures in terms of water supply, quality, flooding and drought. Early detection of these pressures is key to informing adaptation strategies and minimizing adverse environmental and societal impacts.

The National Adaptation Framework (NAF), published by the Department of Communications, Climate Action and Environment, sets out a national strategy for addressing current and future risks posed by climate change. A key element of the plan is to address risks posed by a changing climate to groundwater resources. Groundwater is vital to national water infrastructure, supplying approximately 20-25% of drinking water supplies. In addition, flooding associated with groundwater represents a significant flood hazard for many communities in limestone regions of the country (Naughton, et al., 2017a,b), and a diverse array of wetland ecosystems in Ireland rely on groundwater to sustain habitat structure and function; together these ecosystems represent a significant natural capital resource, providing fundamental ecosystem services such as carbon capture and storage, biodiversity, flood protection and ecotourism (Naughton, 2011, Regan et al., 2019). As a clean, but vulnerable, resource groundwater needs to be better understood, managed and protected.

Geological Survey Ireland, as the national earth science knowledge centre, has proposed addressing this knowledge deficit by establishing a new programme "Climate Change Actions: Groundwater Monitoring and Modelling Response". The aim of the GWClimate project is to quantify the impact that climate change may have on Irish groundwater systems, both in terms of groundwater flooding and drought issues, and monitor groundwater floods using remote sensing to enable short- and long-term forecasting groundwater floods at a national scale. GWClimate intends to enhance the tools developed by GWFlood in order to deliver: 1) further flood maps products, 2) near-real time satellite based hydrographs, 3) groundwater flood forecasting tools, and 4) maps evaluating the impact of climate change in groundwater systems in Ireland. Project outputs will improve the national capacity to understand how groundwater resources respond to climatic stresses and improve the reliability of adaptation planning and predictions in the groundwater sector.

3.1 Methodology

3.1.1 Step up to operational flood Mapping and hydrograph generation

Tools and workflows developed within the GWFlood project are being implemented in a new Python-based workflow for operational flood mapping and hydrograph generation in near real time, increasing the automation (and reducing the human error) of generating the final product. Firstly, automated flood mapping will allow GSI to generate maximum extent flood maps for each flooding season since 2015/16 contributing to quantify the impacts of floods in different areas over the years and regionally monitor the return period of extreme events. Regional differences were already observed between flood events in 2015/16 and 2020 (Figure 10). Although floods in 2015/16 were considered worst-case scenario, recent floods in 2020 were significantly larger in some areas, such as in Glenamaddy. Secondly, automated hydrograph generation will provide key data for monitoring and short-term forecasting of groundwater floods at over 500 sites in Ireland. SAR-generated hydrograph will be available to the public at https://gwlevel.ie/.

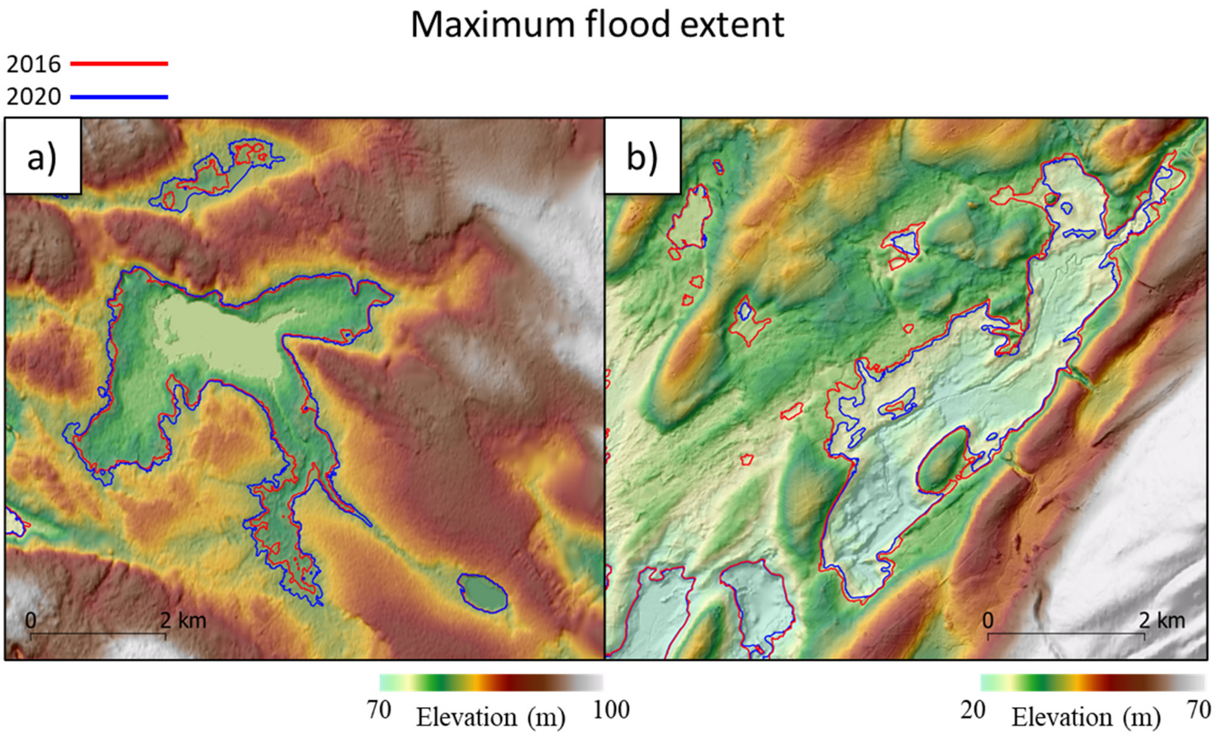

Figure 10: *Comparison of maximum flood extent detected by SAR images between years 2016 (red line) and 2020 (blue line) at a) Glenamaddy Turlough, and b) Blackrock*

3.1.2 Groundwater Flood Forecasting

Whilst flood hazard mapping developed by the GWFlood project are valuable for long-term planning, they do not provide the dynamic information required by communities and local authorities to react to impending flood risks. This project will examine the technical feasibility of groundwater flood forecasting based upon the monitoring (telemetry and remote sensing) and modelling tools developed during the GWFlood project in consultation with the Met Eireann National Flood Forecasting and Warning Service (NFFWS). Forecasting of groundwater flood levels (and likely duration/persistence) could provide critical information regarding impending flood risk, thus enabling communities and relevant authorities to react in a timely manner both before and during groundwater flood events. To work at a national scale the project will focus on global models, starting with the models developed within the GWFlood project and extending the modelling to more complex and adaptable transfer functions (e.g. convolution, classic, and deep machine learning) with the aim to accurately model all sites of interest.

3.1.3 Climate Impacts on Groundwater Systems

This project proposes to examine "Scenario-led" (SL) and "Scenario-neutral" (SN) approaches for the evaluation of climate change impacts on groundwater systems. The SL approach uses outputs from downscaled Global Climate Models (GCMs) to quantify local and regional climate impacts. In contrast, the Scenario-Neutral (SN) approach involves testing the sensitivity of a local indicator (e.g. groundwater level) to incremental adjustments in causative climate variables (e.g. rainfall) across a plausible range of changes in variable intensity and seasonality. A standardised repeatable methodology will be developed for the application and comparison of SL and SN approaches to groundwater systems. It is proposed to pilot the methodology using karst models developed during the GWFlood project, prioritising sites that are vulnerable to impacts of climate.

4. CONCLUSIONS

GWFlood and GWClimate projects are filling the data gap required to understand and quantify groundwater floods in Ireland at a national scale. The main deliverables of these projects (

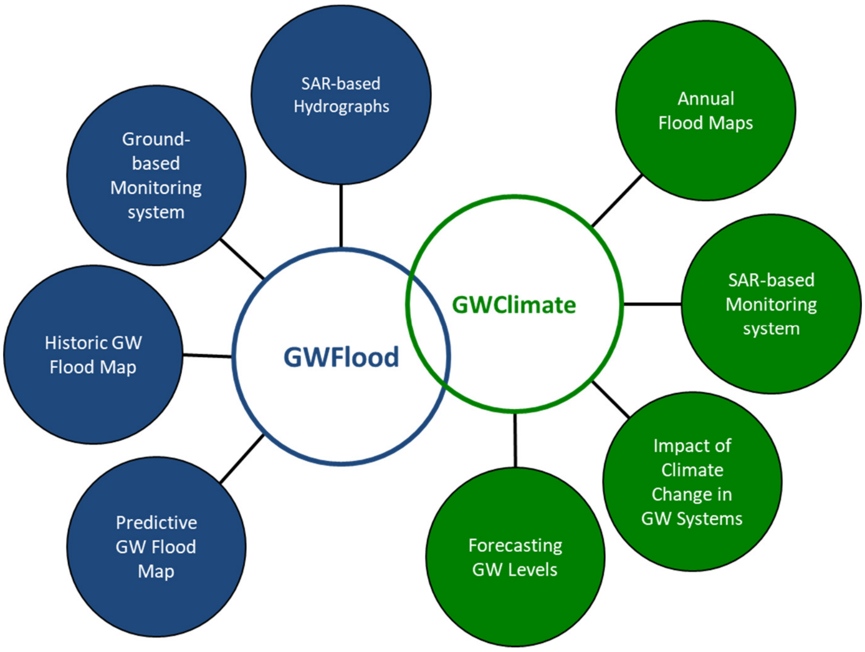

Figure **11**) will inform the scientific community and key stakeholder organisations about the vulnerability of groundwater floods and the potential impact from climate change. GWFlood project has already make a huge progress in addressed the gap in groundwater hydrometric data in Ireland by establishing a permanent telemetric network, as well as developing mapping and modelling tools to address issues surrounding groundwater flood mapping and flood frequency estimation. The supplied outputs, which are freely available on the GSI's website, will enable local and national authorities to make scientifically informed decisions regarding groundwater flood risk management in karst areas. GWClimate project will build on the achievements of the GWFlood project improving the national capacity to understand how groundwater resources respond to climatic stresses and provide relevant data for reducing the impact of future floods. These products will improve the reliability of adaptation planning and predictions in the groundwater sector making Irish society more resilient against floods and the impact of climate change in groundwater systems.

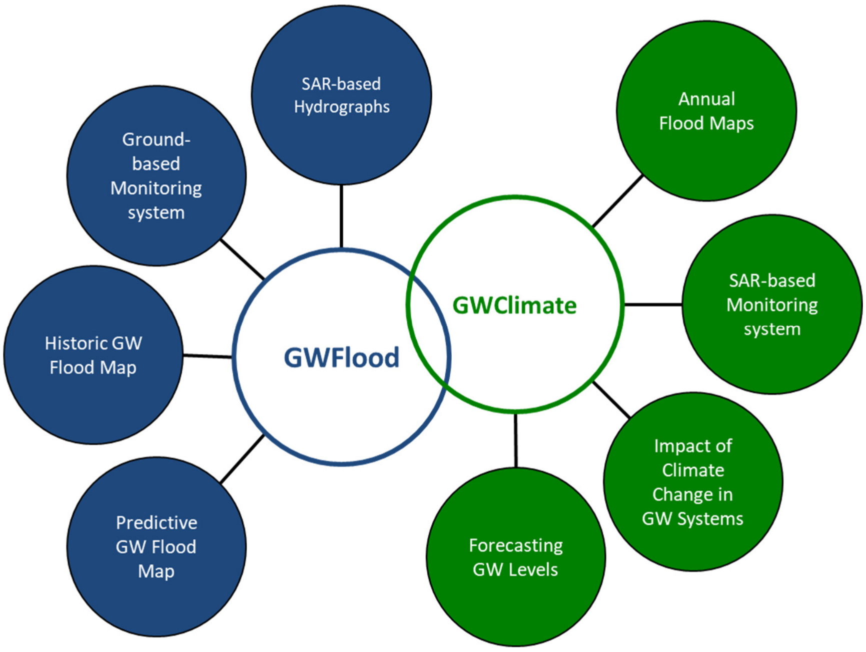

Figure 11: Summary of main products from GWFlood and GWClimate projects

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