02 – Monitoring and mapping groundwater flooding in Ireland

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Abstract

Unprecedented flood events in recent years have 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. In response, Geological Survey Ireland in collaboration with University of Dublin Trinity College has established a new groundwater flood programme (GWFlood) focussed on the issue of turlough flooding.

Key objectives of the GWFlood project are to monitor and map groundwater flooding in Ireland to an unprecedented extent. A monitoring network of over 60 sites has been established over the winter of 2016/2017 to improve our understanding of the hydrodynamics and flooding potential of Irish karst systems. Remote sensing data from Sentinel (ESA) and Landsat (NASA/USGS) satellite programmes are being used to generate high-resolution flood extent maps on a catchment-scale. Time series of Synthetic Aperture Radar (SAR) images are also being combined with high resolution topography maps to construct hydrographs for previously unmonitored sites affected by groundwater flooding.

This new programme will provide the fundamental hydrological data to enable key stakeholders to develop appropriate flood mitigation measures and allow for informed flood assessments to be made in future.

1. INTRODUCTION

The winter of 2015/2016 saw unprecedented levels of rainfall across the Republic of Ireland. Over 600mm of rainfall fell across the island of Ireland between December and February, representing 190% of the long-term average and making it the wettest winter on record in a rainfall time series stretching back to 1850 (McCarthy et al., 2016; Noone et al., 2015). The sustained heavy rainfall caused exceptional and widespread flooding, with rivers across the country bursting their banks and registering some of the highest levels on record. Winter 2015/2016 also saw the most extensive groundwater flooding ever recorded on the karstic limestone plains in the west of Ireland (Figure 1).

Groundwater flooding events in Ireland are primarily associated with the limestone areas of the western lowlands, which extend from the River Fergus in Co. Clare in the south upwards to the areas east of Lough Mask and Corrib in Co. Galway and southern Co. Mayo. The prevalence of groundwater flooding in the western counties is fundamentally linked to bedrock geology. Groundwater flow systems in these areas are characterised by high spatial heterogeneity, low storage, high diffusivity, and extensive interactions between ground and surface waters, which leaves them susceptible to groundwater flooding (Naughton et al., 2015). During intense or prolonged rainfall, the solutionally-enlarged flow paths are unable to drain recharge and available sub-surface storage rapidly reaches capacity. Consequently, surface flooding occurs in low-lying topographic depressions known as turloughs, which represent the principal form of extensive, recurrent groundwater flooding in Ireland (Mott Mc Donald, 2010; Naughton et al., 2012). There are over 400 recorded examples of turloughs across the country, with the majority located in the limestone lowlands in counties Roscommon, Galway, Mayo and Clare. Due to the record breaking rainfall in the winters of 2009 and 2015, turlough flooding impacted on dozens of homes, as well as causing widespread and extended disruption to transport networks across the region.

Unlike fluvial flooding (or fluvially derived groundwater flooding due to seepage along riverbanks), where the flood is typically caused by high intensity rainfall, groundwater flooding is primarily driven by cumulative rainfall over a prolonged period. It is this accumulation of water over a period of weeks or months that determines flood severity and duration. Furthermore, the long-term hydrometric data required for traditional flood frequency analysis does not exist for groundwater flooding, impeding the calculation of flood risk (combination of likelihood of an event and the damage caused by the event) as required in flood defence scheme assessments.

Figure 1: *Groundwater flooding, 2016, South Galway*

2. GEOLOGICAL SURVEY IRELAND GROUNDWATER FLOOD PROJECT

In response to the unprecedented flood events of 2009 and 2015, the Geological Survey has initiated a new programme, GWFlood, to investigate flooding specifically related to groundwater and turloughs. The phenomenon of groundwater flooding can pose a significant flood hazard for many rural communities and its increased frequency in recent years highlights the clear need for further research into the issue of groundwater flood prediction and risk assessment in karst regions. Geological Survey Ireland, in collaboration with Trinity College Dublin is developing a monitoring, mapping and modelling programme to address the knowledge gap regarding these complex karst systems. This programme will enable the OPW and local authorities to develop flood mitigation strategies for groundwater flooding and allow for better informed decisions regarding future groundwater flood risk management. The proposed study aims to provide the requisite data to address this knowledge gap by establishing a permanent monitoring network, as well as developing analytical tools to help address issues surrounding groundwater flood mapping and flood frequency estimation. The main objectives of the project include:

- Establish a permanent monitoring network to provide long-term quantitative groundwater flooding data.
- Develop groundwater flood hazard maps and real-time monitoring of groundwater flooding.
- Develop modelling/analysis methodologies for estimating groundwater flood frequency and the assessment of potential flood mitigation strategies for designated areas.
- Analyse the potential impact of climate change on groundwater flooding.
- Improving general understanding of karst hydrodynamics through targeted studies using multidisciplinary investigation techniques.
- Communicate and disseminate project outputs to key stakeholders.

Two of the primary project deliverables can be summarised under the headings of flood monitoring and flood mapping and are further described below.

3. FLOOD MONITORING

Hydrometric data is a crucial component to understanding the dynamics of surface and groundwater flow systems. Information such as stage and discharge are recorded at gauging stations across the country in rivers, lakes, boreholes and coastlines, providing data vital to local authorities and planning agencies for effective flood risk management. However, consistent long-term hydrometric data do not exist for groundwater flooding applications. A primary objective of this project is thus to establish a monitoring network to provide key baseline data for flood risk and habitat management applications. While some turlough systems posing a flood risk, such as the Gort Lowlands, are relatively well understood there is limited hydrogeological knowledge on most Irish karst groundwater flow systems.

The project commenced in September 2016 and to date, over 60 exploratory monitoring stations have been installed in counties Galway, Clare, Mayo, Roscommon and Longford (Figure 2). Data from these sites will help develop a preliminary understanding of the hydrodynamics and flooding potential of turlough systems across key catchments, and inform the site selection process for the permanent monitoring network. A subset of 20 sites representative of the spectrum of groundwater flooding conditions in Ireland will be established as permanent telemetered stations providing real-time information on groundwater flood conditions. The installation of pilot permanent monitoring stations commenced during summer 2017 and the remaining sites will be installed throughout the summers of 2018 and 2019.

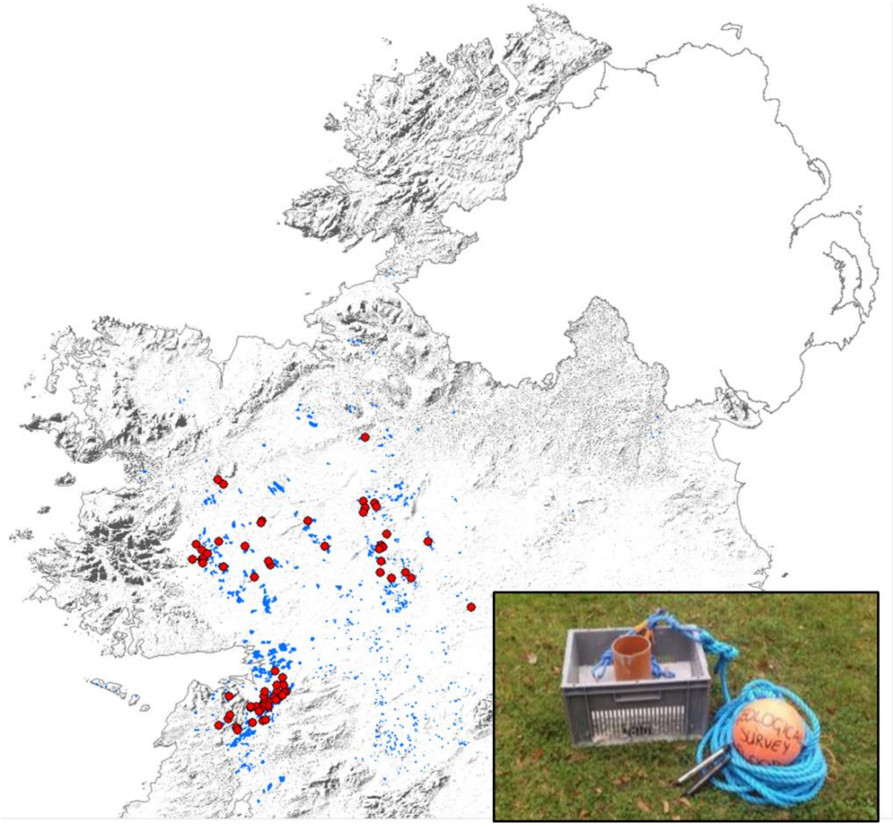
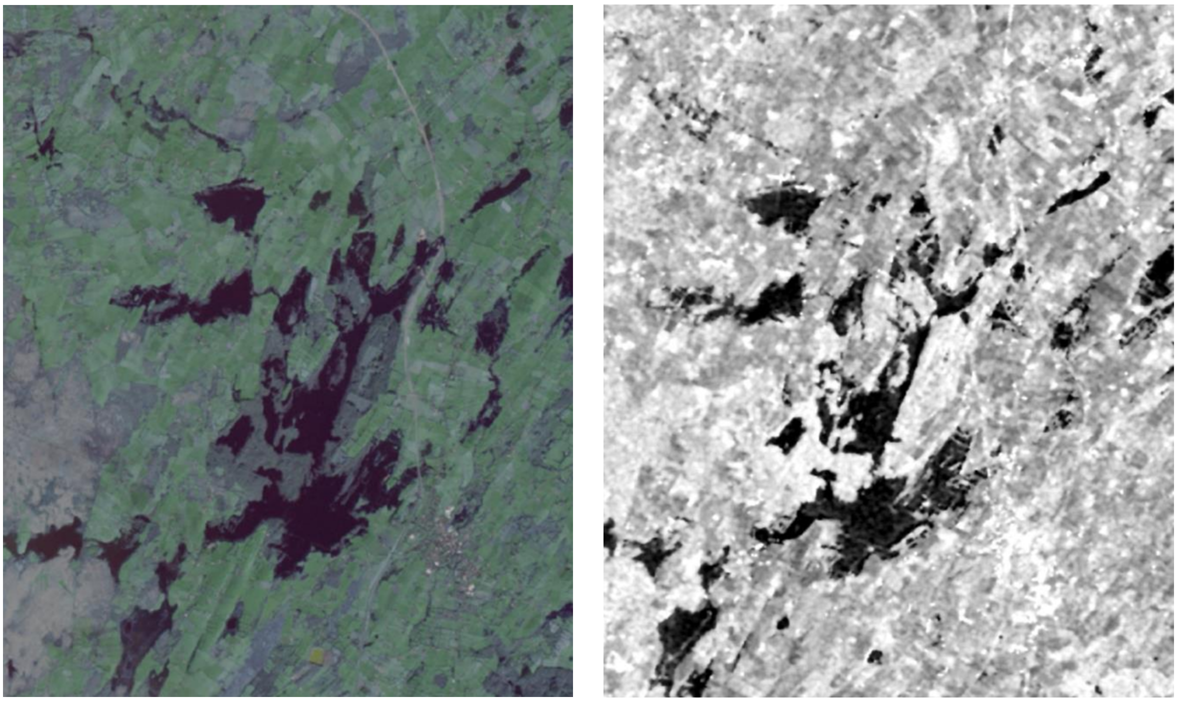


Figure 2: *GWFlood turlough monitoring Network (red) overlaid on groundwater flood hazard sites (blue) (Mott Mc Donald, 2010). Inset: exploratory network monitoring equipment.*

4. FLOOD MAPPING

The ability to describe and map how floods develop and recede accurately and at a large spatial scale is a prerequisite for effective flood risk management. This poses significant problems for monitoring groundwater flooding, however, as 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 Geographical Information System (GIS) approaches offer significant advantages in this respect. Passive satellite imagery, such as the USGS Landsat or ESA Sentinel-2 programmes, can be used to image and delineate floods at a catchment scale (Figure 3). In the case of Landsat, a long historical archive of images also allows us to look at past flood conditions and provides some data with which to validate hydrological models. However, an obvious limitation of satellite systems which 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 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 impacted by cloud cover.

SAR systems, such as those used by ESA Sentinel-1 satellites, emit radar pulses and record the return signal at the satellite. This 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. Interpretation of SAR images involves a degree of ambiguity due to factors such as speckle effects and dielectric properties but overall SAR systems offer a powerful tool for water delineation. An additional benefit of SAR is the frequency of image capture; the ESA Sentinel-1 satellites collect SAR images over Ireland at every three to six days dating back to 2014 and so provide high temporal resolution with which to map groundwater flood events.



(A): Landsat-8 imagery of flooding near Gort, February 2016.

(B) Sentinel-1 SAR imagery of flooding near Gort, February 2016.

Figure 3: *Landsat-8 and Sentinel-1 comparison imagery of flooding near Gort town, February 2016*

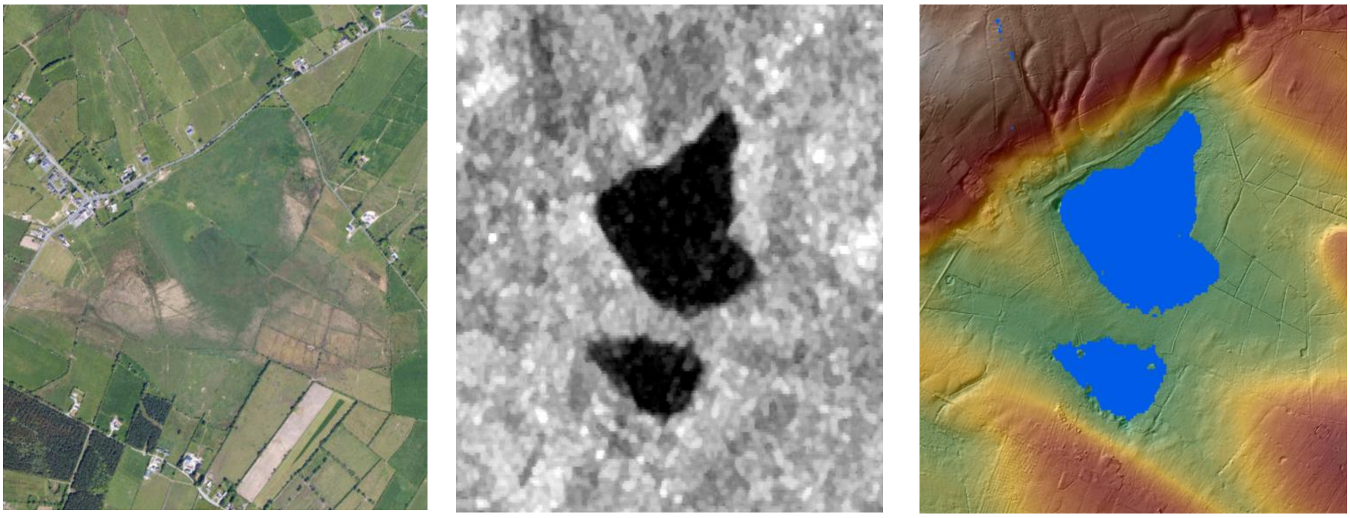
Numerous studies have demonstrated the efficacy of delineating water bodies using SAR remotely-sensed data (Amitrano et al., 2014; Hostache et al., 2012; Martinis et al., 2015). Similar image processing techniques are being trialled and developed under the GWFlood project to optimise detection of groundwater flood extents from SAR data. By combining satellite derived flood extents with high resolution topographic mapping, it is possible to extract water level information from each satellite image. This methodology enhances the accuracy of once-off flood extent maps as well as enabling the generation of historic flood hydrographs for previously unmonitored sites. This flood mapping methodology consists of five stages:

4.1 Data acquisition and pre-processing

Sentinel 1 Ground Range Detected (GRD) data is downloaded in batch via API from ESA Copernicus Open Access Hub and run through a series of pre-processing steps. These steps include slice assembly, border noise removal, thermal noise removal, radiometric calibration, terrain correction, co-registration and speckle filtering. Once pre-processing is complete, the images are then exported into GIS software for flood delineation.

4.2 Flood delineation

Several methodologies exist to delineate water from SAR imagery. These include visual interpretation (Brivio et al., 2002), histogram thresholding (Matgen et al., 2011), supervised classification (Pulvirenti et al., 2011), change detection (Rémi and Hervé, 2007) and various image texture algorithms (Schumann et al., 2010). A number of these methods have been successfully trialled for turlough applications however the most suitable method is still under consideration. In general, delineation accuracy is improved with increased complexity and greater user interaction (and thus a degree of unrepeatable ambiguity). The process under development for turlough water delineation however is intended to be near fully automated, and as such, the delineation method will be chosen will be as unsupervised as possible (with minimum errors). Currently, the most appropriate method under consideration is a combined process of histogram thresholding, change detection and fuzzy logic (i.e. computing based on 'degrees of truth' rather than Boolean 'true' or 'false' logic). The end result of this process is a classification for each pixel identifying whether the pixel represents flooded or non-flooded conditions (Figure 4).

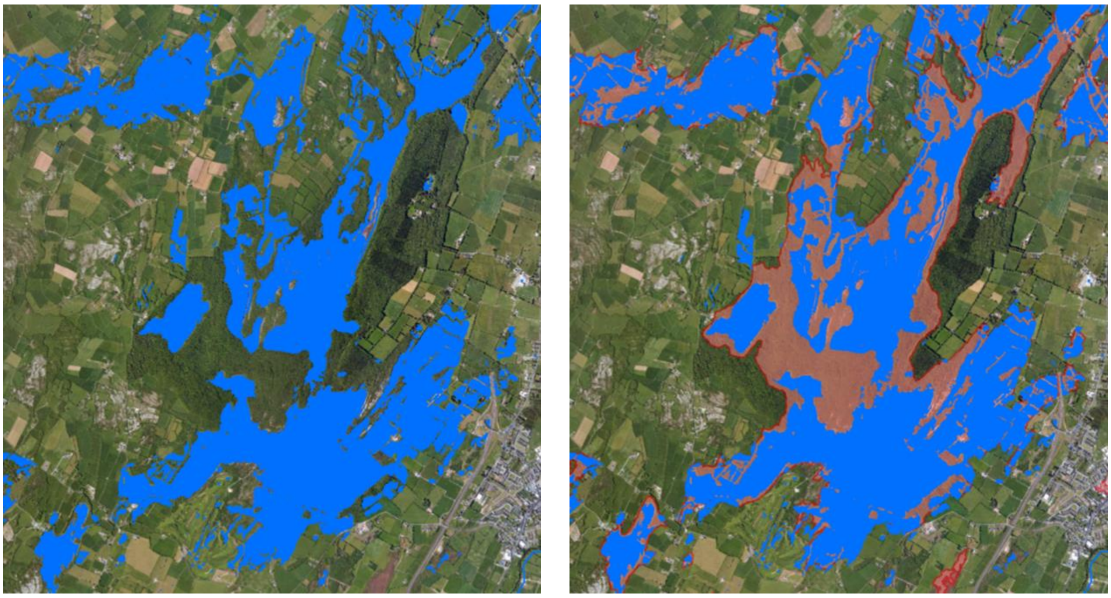


(A): Orthophotography *(B): SAR imagery, March 2017* *(B): Flood delineation, March 2017*

Figure 4: *Imagery of Castleplunket turlough Co. Roscommon showing orthophotography of it empty (A), pre-processed SAR imagery of it flooded (B) and a flood delineation overlaid on LiDAR data (C)*

4.3 Image filtering & correction

The interpretation of SAR imagery is subject to a level of ambiguity due to a number of inherent factors. This ambiguity can often result in misclassification of which pixels are flooded and which ones are not (i.e. false negative and false positive results). For example, radar shadowing due to local topography often results in false positive pixels on leeward hillsides (i.e. flooding is identified on the side of a slope that the side-looking Sentinel-1 sensor cannot see). These radar shadow errors are being filtered out based on a derived height above nearest drainage (HAND) dataset which represents the topographic difference between a pixel and its nearest water course (Nobre et al., 2016). This filtering process removes flooded pixels from areas which are very unlikely to flood due to their topographic setting. Another example of ambiguity is that of forested areas causing false negatives. A flooded forest is identified as non-flooded due to geometric distortion from the tree canopy which produces increased backscatter. While this increased backscatter can be exploited by horizontally polarised (HH) SAR systems to map the flooded forests, Sentinel 1 only collects dual vertically polarised (VV&VH) datasets over the majority of Ireland which is not as efficient at flooded forest detection (Townsend, 2002). This results in an underestimation of flood extent at forested margins of turlough sites due to false negative pixels (Figure 5) In order to avoid this source of error, only non-forested areas surrounding turloughs are used for further analysis. In the event of a turlough being completely surrounded by forestry, the remote sensing derived data is complimented by physical monitoring data.



(A): SAR delineated flood only. *(B): SAR delineation and actual flood extent.*

Figure 5: *Comparison of SAR delineated flood extent vs. actual flood extent, Coole turlough, Co. Galway, January 2016*

4.4 Application of Topography

After filtering out likely errors, the delineated flood extent is cross referenced with a high resolution digital topography map (DTM) to provide contextual information. This methodology benefits from the fact that turlough flooding typically occurs in enclosed, isolated basins. As a result, and unlike river flooding scenarios, the water surface is usually flat. In theory, this means that every pixel along the flood boundary should have the same elevation on the DTM. However in reality the values vary over a distribution of possible elevation values

(Figure 6) due to a range of factors, the most significant of which is the relatively poor pixel resolution (10m) of SAR data compared with high resolution DTMs (1-2m LiDAR in many cases). Statistical analysis is preformed over the elevation values to establish which value within the distribution is the most probable. When this likely flood elevation value is calculated, the flood boundary can subsequently be remapped based on the given elevation value's contour produced from the DTM.

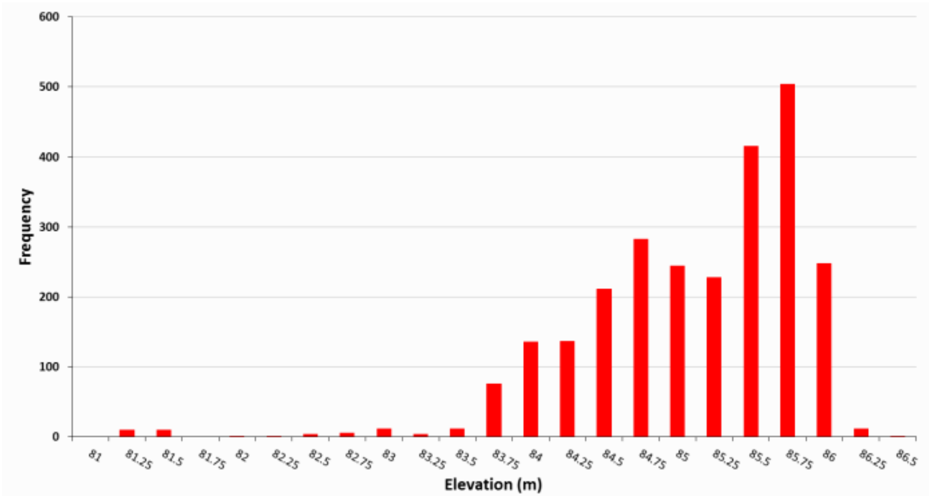


Figure 6*: Distribution of elevation values associated with delineated flood boundary for Castleplunket turlough, Co. Roscommon, 19th March 2017*

4.5 Map and hydrograph generation

With the pre-processing, delineation, filtering and DTM application stages complete the flood map is generated. A maximum flood extent map for any given flood event can be generated using the time appropriate satellite images. Furthermore, the process can be repeated for every satellite flyover enabling the generation of dynamic flood mapping and hydrograph generation for specific sites. Preliminary results of this hydrograph generation process are promising however the delineated flood levels tend to be underestimated at higher elevations (Figure 7). The primary cause for this underestimation is likely to be the speckle filter stage during pre-processing. Work is on-going to minimise this error and automate the delineation methodology. This is being accomplished using the data records from the monitoring network to compare with the SAR data for a given time (Figure 8). With these records, delineation accuracy can be checked and the delineation method can be calibrated.

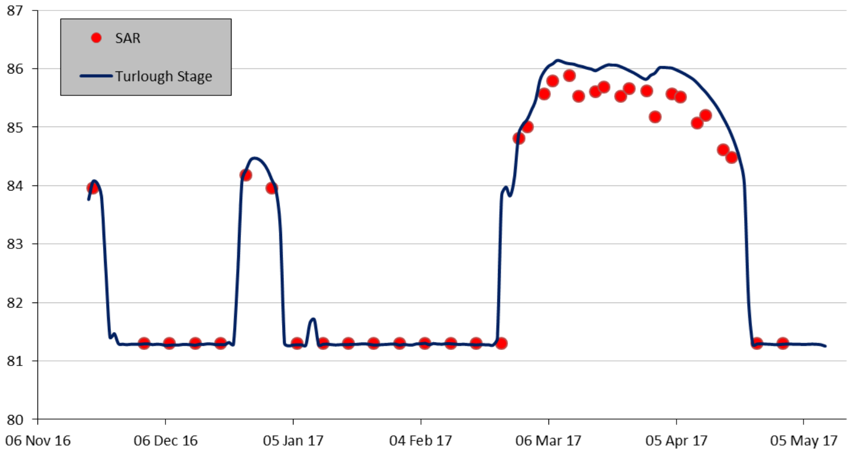


Figure 7: *Comparison of directly observed water levels vs. SAR generated water levels at Castleplunket turlough, Co. Roscommon*

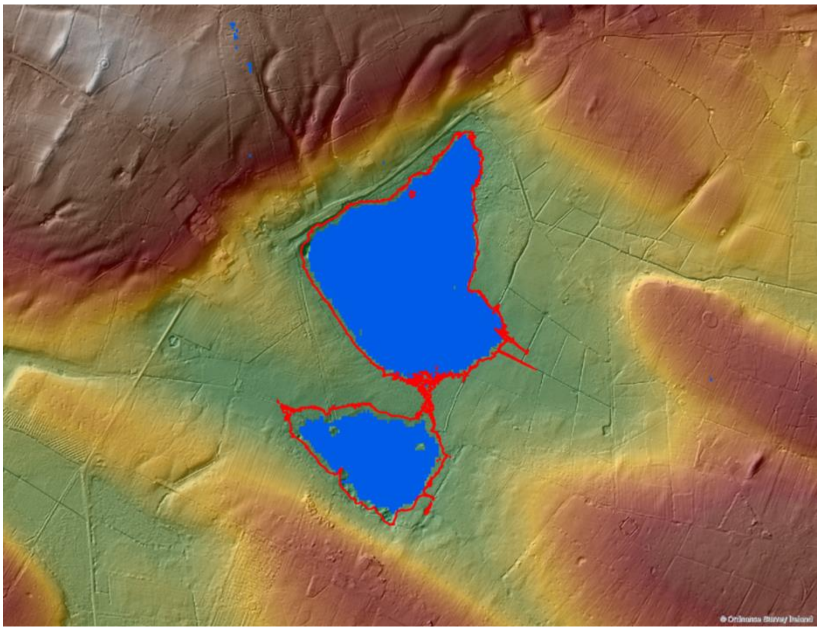


Figure 8: Comparison of SAR delineated flood extent (blue) and directly observed flood extent (red) at Castleplunket turlough, 19th March 2017

5. SUMMARY

The increased frequency, damage and disruption caused by turlough flood events in recent years highlights the clear need for further research into the issue of groundwater flood prediction and risk assessment in karst regions. Due to the inherent complexity of karst groundwater systems and the lack of quantitative hydrological data available, the GWFlood project presents a unique opportunity to use a knowledge base gained over the last decade to contribute to flood risk management practices in Ireland. The project is installing an extensive groundwater flood monitoring network and using innovative mapping techniques to collect information on groundwater flooding at an unprecedented scale. This information will then be used in the development of hydrological models which will enable the estimation of groundwater flood return periods. The project will provide the necessary high-quality data, mapping and analysis techniques required to inform future planning decisions, and so help to ensure the sustainability of vulnerable rural communities affected by groundwater flooding as well as the turlough habitats themselves. The project will influence policy and governance by giving decision makers more information on the drivers and mechanisms of groundwater flooding in Irish karst systems, and allow them to make scientifically-informed decisions for better outcomes within the Floods, Water Framework and Habitats Directives.

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