08 – Developing historic and predictive groundwater flood maps for Ireland

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Abstract
Identifying and mapping areas vulnerable to flooding is a key step in the management of flood risks. However, the nature of groundwater flooding on the lowland karst limestone plains of Ireland pose significant technical challenges in this respect. These areas are susceptible to groundwater flooding due to the combination of low soil and aquifer storage, high diffusivity and limited surface drainage. Unprecedented flooding in winter 2015/2016 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.

This paper describes the novel approach developed to produce historic and predictive groundwater flood maps for Ireland in line with the 2nd implementation cycle of the EU Floods Directive. A monitoring network of over 50 sites was established during the winter of 2016/2017 to improve our understanding of groundwater flood regimes and provide baseline model calibration data. A methodology for delineating flood extents and water elevations from multi-temporal Synthetic Aperture Radar (SAR) imagery was developed to provide flood data from the 2015/2016 extreme flood event at gauged and ungauged sites. Maximum flood extents derived from SAR imagery from this event were combined with limited field observations to produce historic groundwater flood maps.

Hydrological models capable of reproducing groundwater flooding time series from antecedent rainfall and soil moisture conditions were developed. Models for viable groundwater flooding locations were calibrated on a combination of observed and SAR hydrographs. Using long-term observational and stochastic meteorological series as input, the models have been used to construct long-term hydrological series suitable for extreme value analysis and the generation of predictive groundwater flood extents and maps.

1. INTRODUCTION

Floods are natural phenomena which cannot be completely prevented; they have the potential to cause fatalities, damage property and infrastructure, and compromise economic development (Directive 2007/60/EC). 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.*, 2016). 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. The winter also saw the most extensive groundwater flooding ever witnessed on the karstic limestone plains in the west of Ireland (Naughton *et al*., 2017b). Here homes were flooded or cut off, roads submerged, and agriculture disrupted, with some affected areas remaining inundated for months after flooding had subsided elsewhere.

Groundwater flooding in Ireland is 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.*, 2017a). 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 MacDonald, 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.

The literature on groundwater flooding remains comparatively sparse in contrast to fluvial and pluvial flooding with relatively limited reporting of the phenomenon worldwide (Abboud *et al.*; Finch *et al.*, 2004; Gotkowitz *et al.*, 2014; Hughes *et al.*, 2011). However, attention on groundwater flooding as a geohazard has increased in recent decades due to an increased frequency of extreme groundwater flood events across Europe (Ascott *et al.*, 2017; Finch *et al.*, 2004; Naughton *et al.*, 2017b; Pinault *et al.*, 2005). The introduction of the EU Floods Directive (2007/60/EC), requiring States to consider flooding from groundwater sources, has reinforced the need to improve our understanding of the processes influencing this phenomenon. This is particularly the case of the karst limestone lowlands of Ireland; this paper will give an overview of the methodology developed for historic and predictive groundwater flood mapping in these regions.

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 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 new three-year project on groundwater flooding.

Geological Survey Ireland, in collaboration with Trinity College Dublin and Institute of Technology Carlow have developed a monitoring, mapping and modelling programme to address the knowledge gap regarding these complex karst systems. The study is providing the requisite data to address the gap in groundwater hydrometric data by establishing a permanent telemetric network, as well as developing modelling tools to help address issues surrounding groundwater flood mapping and flood frequency estimation. A key output from this project is to devise and implement a novel approach to produce historic and predictive groundwater flood maps for Ireland in line with the 2nd implementation cycle of the EU Floods Directive.

The EU Floods Directive (Directive 2007/60/EC) requires all Member States including Ireland to reduce and manage the risks that all forms of flooding pose through the mapping of probabilistic flood extents and the establishment of flood risk management plans. For flooding from groundwater sources, the Floods Directive stipulates that Member States may decide that the preparation of flood hazard maps shall be limited to the scenario floods with a low probability, or extreme event scenarios. This was the approach taken for groundwater flood mapping during the first implementation phase of the Floods

Directive, where an evidence-based method was used to map areas vulnerable to groundwater flooding (Mott Mc Donald, 2010). After the extensive flooding of the winter of 2015/2016 there was a requirement to incorporate this new information into updated historic groundwater flood maps. Furthermore, considering the increased frequency of groundwater flooding in recent decades, methodologies for the estimation of flood frequency would also provide a valuable tool for groundwater flood management.

It is in this context that the GWFlood project has developed a groundwater flood mapping methodology for gauged and ungauged sites, which includes the first approach to groundwater flood frequency estimation undertaken in the State. Two types of flood maps are being developed. The first, the historic flood map, shows the extent of observed groundwater flood events and is largely based on mapping of the 2015/2016 event combined with observed flood information gathered during the first PFRA. Predictive flood maps have also been developed for areas of recurrent groundwater flooding (turloughs), with flood levels and extents predicted for a range of annual exceedance probabilities (AEP).

2. HYDROLOGICAL DATA COLLECTION

A prerequisite for both the historic and predictive flood maps is observation data. Historically there has been no systematic collection of hydrometric data of groundwater flooding, however, and so the required data do not exist. To address this information gap, the GWFlood project has:

- Established a monitoring network to provide baseline hydrometric data for significant/representative sites.
- Developed a remote sensing procedure which uses Synthetic Aperture Radar (SAR) imagery for the delineation of floods at ungauged sites and during the 2015/2016 extreme floods.

2.1 Field Hydrological Monitoring

Hydrometric data is a crucial component to understanding the dynamics of surface and groundwater flow systems. Hydrometric information such as stage and discharge are recorded across the country in rivers, lakes 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 the GWFlood project was to establish a monitoring network to provide this baseline data.

Installation of monitoring infrastructure commenced in September 2016 and over 60 exploratory monitoring stations were installed in counties Galway, Clare, Mayo, Roscommon, Longford and Westmeath (Figure 1). Data from these sites are helping to develop an understanding of the hydrodynamics and flooding potential of turlough systems across key catchments and provide model calibration data. Exploratory data have also been used to inform the site selection process for the permanent monitoring network. A subset of 20 sites representative of the spectrum of groundwater flooding conditions is being established as permanent telemetered stations providing real-time information on groundwater flood conditions. The installation of permanent monitoring stations began in summer 2017 and is scheduled for completion by mid-2019.

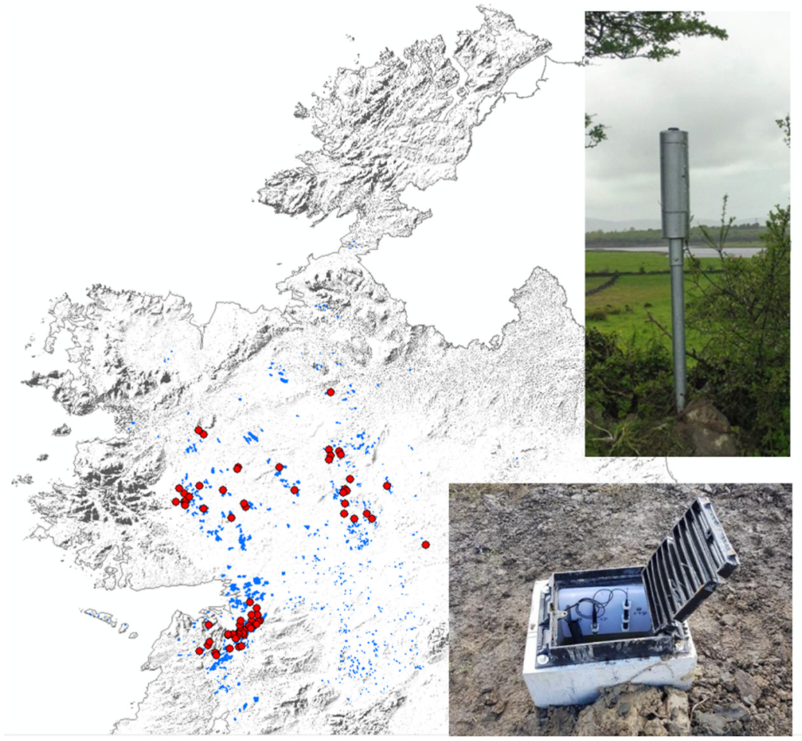
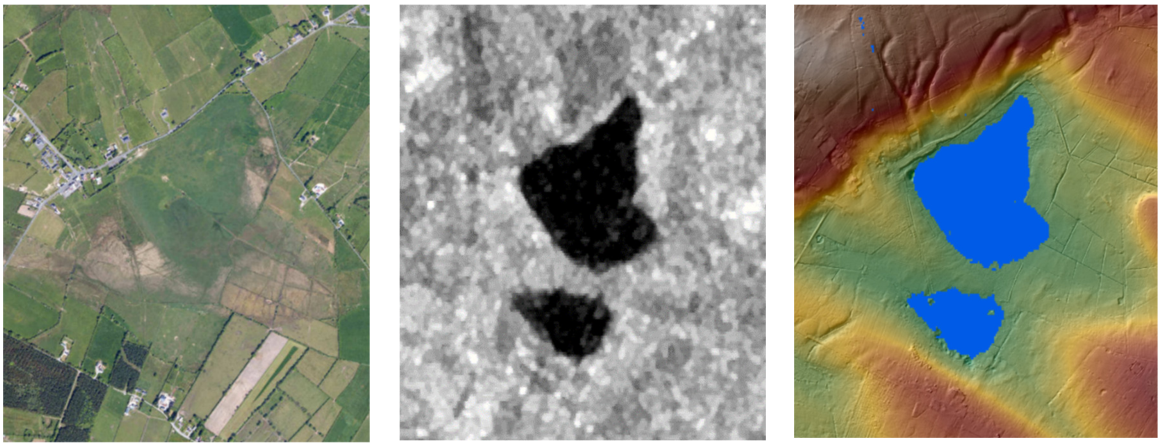


Figure 1: *GWFlood Turlough Monitoring Network (red) overlaid on groundwater flood hazard sites (blue) (Mott MacDonald, 2010). Insets: Telemetric monitoring equipment.*

2.2 Remote Sensing Hydrological Monitoring

While traditional monitoring is an effective tool for hydrometric data collection at priority sites, the distributed nature of groundwater flooding in karst lowlands hampers any systematic mapping efforts. Groundwater flooding occurs in isolated basins across the landscape. The large number and wide distribution of these basins makes them impractical to monitor using field instrumentation. Earth Observation and Geographical Information System (GIS) approaches offer significant advantages in this respect. 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.

Active systems, such as synthetic aperture radar (SAR), are particularly useful for flood mapping as they have a day-and-night capability and are not impacted by cloud cover. SAR systems emit radar pulses and record the return signal at the satellite. Flat surfaces such as water operate as specular reflectors for the radar pulses resulting in minimal backscatter signal returning to the satellite thus providing a contrast between dry and flooded areas (Figure 2). While interpretation of SAR images involves a degree of ambiguity due to factors such as speckle effects and dielectric properties, overall SAR systems offer a powerful tool for water delineation.



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

Figure 2: *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*

The information gained from SAR imagery can be further enhanced by adding contextual information from high-resolution topographic mapping. The flood boundary can be cross-referenced against the topographic data to calculate the elevation of the land-water interface and thus the depth of water in the turlough. 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 can be assumed to have a uniform elevation value.

An additional benefit of Sentinel-1 is the frequency of image capture; the satellites have been collecting imagery over Ireland at a 1 to 3 day revisit time since late 2014. While this revisit time may be inadequate for observing flash floods, which appear and dissipate within hours, it is suitable for monitoring groundwater flooding which occurs at a much slower rate (weeks to months). The considerable catalogue of Sentinel-1 imagery available has allowed us to track groundwater flood development through time. For sites with suitable size and topography characteristics the depth calculation process can be repeated for every satellite orbit enabling the generation of dynamic flood mapping and hydrographs (Figure).

Image processing techniques have been developed by the GSI in-house 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. The flood mapping methodology consists of five broad stages:

1. Data acquisition and pre-processing
2. Flood delineation using an automated, repeatable image thresholding algorithm
3. Image filtering & correction
4. Application of topography to establish the most probable land-flood interface elevation value.
5. Map and hydrograph generation

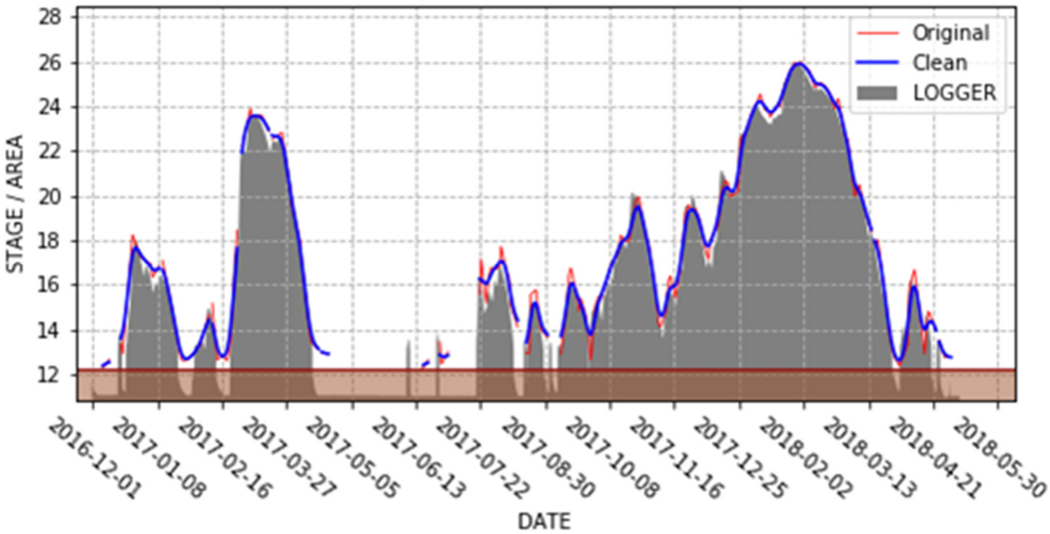


Figure 3: *Observed (grey) and Sentinel-1 derived hydrograph (blue) for Blackrock Turlough, Co. Galway*

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. 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 approach. 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 input and actual evapotranspiration (ET_A) and effective rainfall or recharge (R_E) as 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 Antecedent Precipitation Index (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:

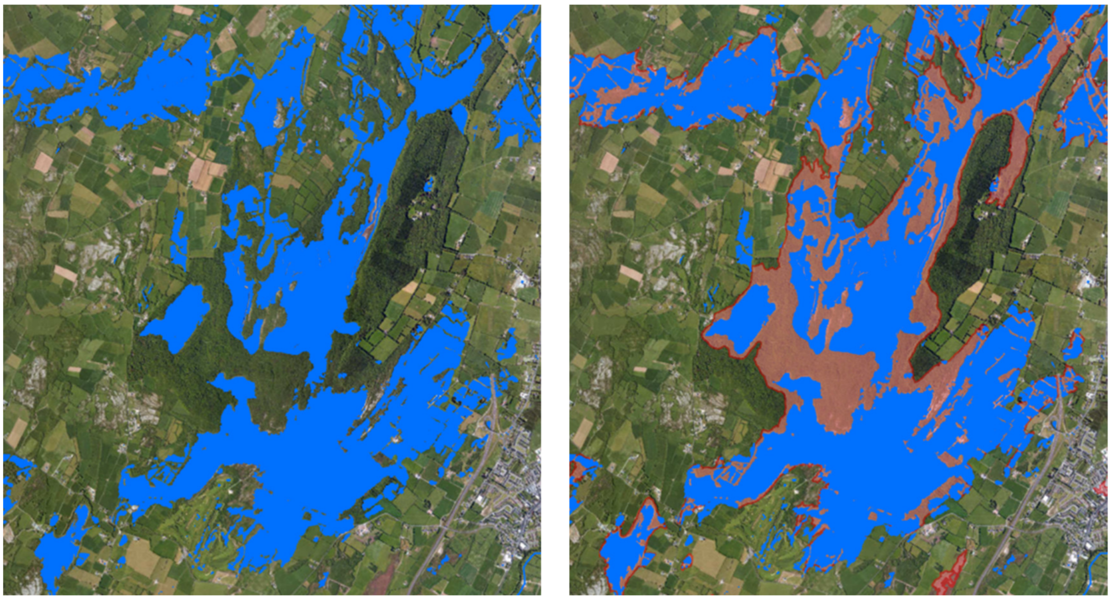
$$CPI = \sum_{t=-1}^{-i} P_t k^{-t}$$

Where i is the number of antecedent days, k is a decay constant and P_t is rainfall on day t. 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 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

4.1 Historic Flood Map

The historic flood map shows the extent of observed groundwater flood events in karst areas; it is largely based on mapping of the 2015/2016 event using Sentinel-1 SAR combined with observed flood information gathered during the 2015/2016 event and the first PFRA. The water delineation process described in section 2.1 is applied to every Sentinel-1 SAR image available for 2015/2016 winter period. These images are filtered for noise and qualifying criteria (e.g. radar shadow, karst/non-karst regions) and the maximum spatial extent of flooding during the period is delineated. Where recurrent flooding is detected and the turlough basin meets the criteria for topographic correction, an additional water delineation stage is applied to the series of SAR images for each qualifying basin. This process estimates a peak flood elevation for each SAR image, rather than solely classifying each pixel into water and non-water. A maximum flood contour is then derived from a digital terrain model using the highest observed flood level in the SAR-generated hydrograph. An advantage of this approach is that it gives both an elevation and a more accurate representation of flood extent; for example, it can overcome some of the limitations of C-band SAR such as an inability to identify areas of flooded forestry (Figure 4). Once SAR water delineation is complete, all maximum flood extents are combined with any readily-available historic information on groundwater flood extents in karst areas into a historic flood map GIS layer.



(A): SAR delineated flood only (forestry obscures some flooding). *(B): SAR delineation and actual flood extent.*

Figure 4: *Comparison of SAR delineated flood extent vs. actual flood extent, Coole Turlough, Co. Galway, January 2016.*

4.2 Predictive Flood Map

The conceptual approach to predictive groundwater flood mapping is shown in Figure 5. The process ties together the observed and SAR-derived hydrograph data, hydrological modelling, stochastic weather generation and extreme value analysis to generate predictive groundwater flood maps for qualifying sites. The overall objective of the method is to generate a hydrological record of sufficient length to estimate the magnitude and frequency of extreme groundwater flood events.

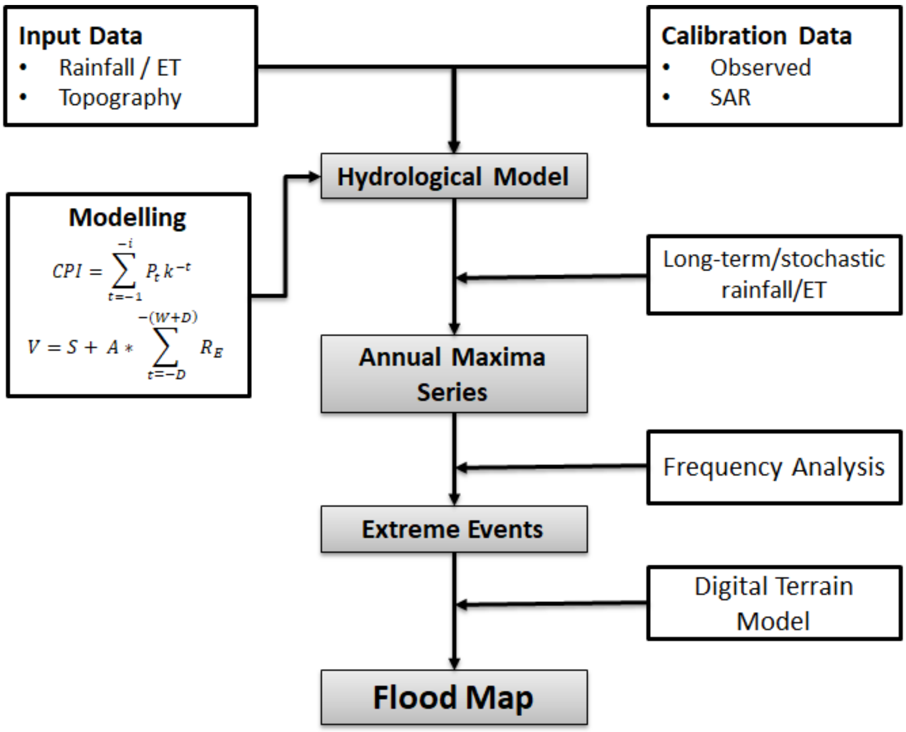


Figure 5: *Flow chart for predictive groundwater flood mapping methodology.*

First, a site-specific hydrological model capable of reproducing groundwater flooding time series from antecedent rainfall and soil moisture conditions is calibrated using a combination of observed (where available) and SAR hydrographic data. Long-term meteorological series are then used as model input to construct long-term volume time series suitable for flood frequency analysis. Observational rainfall records are not sufficient long for the estimation of extreme flood events. To overcome this limitation, a stochastic weather generator is used (Chen *et al.*, 2010). Stochastic weather generation uses existing weather records to produce synthetic weather series of unlimited length, thus permitting impact studies of rare occurrences of meteorological variables. (Chen *et al.*, 2010). A stochastic weather generator algorithm (Chen *et al.*, 2010) is calibrated using observed meteorological data from Met Eireann stations, and used to generate long-term (1000+ year) synthetic rainfall data for each site. This stochastic time series, together with long-term average evapotranspiration (ET), are used as input data to the site model to produce a long-term volume time series. A statistical distribution is fitted to the annual maxima and the generation of predictive groundwater flood extents and maps (Figure 6).

Figure 6: *10%, 1% and 0.1% Annual Exceedance Probability flood extents at Castleplunket turlough.*

5. ACKNOWLEDGEMENTS

This work was supported by the Geological Survey of Ireland, Office of Public Works and the Irish Research Council. The authors would also like to thank the Irish Meteorological Service (Met Eireann) for the provision of rainfall data, Galway County Council for the provision of aerial photography and GIS data, and the Office of Public Works for the provision of LIDAR, hydrometric and aerial photography data.

6. REFERENCES

Abboud, J.M., Cathryn Ryan, M., Osborn, G.D., Groundwater Flooding in a River‐Connected Alluvial Aquifer. Journal of Flood Risk Management.

Ascott, M., Marchant, B., Macdonald, D., McKenzie, A., Bloomfield, J., 2017. Improved understanding of spatiotemporal controls on regional scale groundwater flooding using hydrograph analysis and impulse response functions. Hydrological Processes.

Beschta, R.L., 1998. Forest hydrology in the Pacific Northwest: additional research needs. JAWRA Journal of the American Water Resources Association, 34(4): 729-741.

Chen, J., Brissette, F.P., Leconte, R., 2010. A daily stochastic weather generator for preserving low-frequency of climate variability. Journal of hydrology, 388(3-4): 480-490.

Finch, J.W., Bradford, R.B., Hudson, J.A., 2004. The spatial distribution of groundwater flooding in a chalk catchment in southern England. Hydrological Processes, 18(959-971).

Gotkowitz, M.B., Attig, J.W., McDermott, T., 2014. Groundwater flood of a river terrace in southwest Wisconsin, USA. Hydrogeology Journal, 22(6): 1421-1432.

Hughes, A.G. et al., 2011. Flood risk from groundwater: examples from a Chalk catchment in southern England. Journal of Flood Risk Management, 4(3): 143-155.

Kohler, M.A., Linsley, R.K., 1951. Predicting the runoff from storm rainfall, 30. US Department of Commerce, Weather Bureau.

Kovacs, A., Sauter, M., 2007. Modelling karst hydrodynamics. In: Goldscheider, N., Drew, D. (Eds.), Methods in karst hydrogeology. IAH international contributions to hydrogeology 26. Taylor & Francis, pp. 201-222.

McCarthy, M., Spillane, S., Walsh, S., Kendon, M., 2016. The meteorology of the exceptional winter of 2015/2016 across the UK and Ireland. Weather, 71(12): 305-313. DOI:doi:10.1002/wea.2823

Mott MacDonald, 2010. Preliminary Flood Risk Assessments: Groundwater Flooding, Dublin.

Mott Mc Donald, 2010. Preliminary Flood Risk Assessments - Groundwater Flooding. Prepared for the Office of Public Works, Dublin.

Naughton, O., Johnston, P.M., Gill, L.W., 2012. Groundwater flooding in Irish karst: The hydrological characterisation of ephemeral lakes (turloughs). Journal of Hydrology, 470–471(0): 82-97. DOI:10.1016/j.jhydrol.2012.08.012

Naughton, O., Johnston, P.M., McCormack, T., Gill, L.W., 2017a. Groundwater flood risk mapping and management: examples from a lowland karst catchment in Ireland. Journal of Flood Risk Management, 10(1): 53-64. DOI:10.1111/jfr3.12145

Naughton, O., McCormack, T., Gill, L., Johnston, P., 2017b. Groundwater flood hazards and mechanisms in lowland karst terrains. Geological Society, London, Special Publications, 466: SP466. 9.

Noone, S. et al., 2016. Homogenization and analysis of an expanded long‐term monthly rainfall network for the Island of Ireland (1850–2010). International Journal of Climatology, 36(8): 2837-2853. DOI:doi:10.1002/joc.4522

Pinault, J.L., Amraoui, N., Golaz, C., 2005. Groundwater-induced flooding in macropore-dominated hydrological system in the context of climate changes. Water Resources Research, 41(W05001, doi:10.1029/2004WR003169).

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

Smakhtin, V.Y., Masse, B., 2000. Continuous daily hydrograph simulation using duration curves of a precipitation index.