09 – Groundwater flood modelling in the karst lowlands of south Galway

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Abstract

The Gort lowlands catchment covers an area of approximately 500km^2 in south Co. Galway on the western coast of Ireland. Three river systems discharge runoff from adjacent mountains to the lowland catchment and another smaller river drains to the catchment from the border of the Burren limestone pavement to the south. The surface hydrology of the Gort lowlands becomes extremely complex once these four rivers flow into the catchment due to the karstified nature of the limestone bedrock. The hydrogeology and surface hydrology of the Gort Lowlands are therefore closely linked due to the extensive bedrock karstification with water exchanged between the surface and subsurface in large volumes throughout the catchment through sinking streams (swallow holes), large springs and river risings. The entire catchment drains to a number of intertidal springs at Kinvara Bay through the karst limestone bedrock. During periods of sustained rainfall, the underground karst conduit system surcharges to the ground surface through a system of estavelles and floods low lying areas of ground known as turloughs. These turloughs provide additional storage of groundwater when sufficient capacity is not available in the bedrock. Some limited fluvial flooding occurs across the catchment, however, given the nature of the lowlands, any fluvial flooding is intimately linked to associated groundwater flooding.

Extensive flooding associated with turloughs across the Gort lowlands occurred in November 2009 and December 2015/January 2016 which led to considerable damage, disruption and hardship for local residents and farmers. Over 24km^2 of land was flooded for up to 6 months with many residents and farms cut-off due to roads being impassable for extended periods. As a result of the most recent flood event in 2015/2016 a new research project, which is a collaboration between Trinity College Dublin (TCD) and Geological Survey Ireland (GSI), was initiated which aimed to better understand the occurrence and behaviour of these flood events with a view to providing insight and guidance for relevant authorities to investigate potential alleviation measures. Limited records and detail of groundwater flooding within the catchment is available and, coupled with a lack of data in relation to the surface hydrology, has led to a complex and unique research task. A pipe network model of the karst conduit system of the Gort lowlands has been developed by TCD in order to simulate the flooding mechanism of a series of turloughs across the Gort lowlands. The availability of high accuracy LiDAR data of the catchment topography allowed the flooding regime to be accurately simulated on the ground surface quantifying overland flooding. The availability of additional flood stage data from a number of turloughs, along with simulated data from satellite imagery collected and modelled by the GSI, allowed further understanding and definition of the groundwater flood mechanisms. A methodology was then developed which allowed groundwater flooding return periods (Annual Exceedance Probabilities) to be estimated for past and future events using the calibrated model. The model is now being used to estimate the effects of drainage works and defences across the catchment in the context that the normal flooding regime of these sensitive wetland habitats must be maintained.

1. INTRODUCTION

Groundwater flooding events in Ireland predominantly occur within the lowland limestone areas of the west of the country. This flooding is inherently linked to the underlying bedrock geology. Extensive interactions between ground and surface waters are predominant with sinking and rising rivers/streams common with surface water features absent completely in many areas. The dominant drainage path for many catchments is via bedrock through the karstified limestone bedrock, however during intense or prolonged rainfall the fractures or conduits within the limestone are unable to drain recharge and with storage within the bedrock limited, the result is surcharging of groundwater above the surface. This flood water is usually contained within low-lying topographic depressions known as turloughs, which represent the principal form of extensive, recurrent groundwater flooding in Ireland (Naughton et al., 2017).

The large volumes involved and long-lasting nature of the flooding associated with these turloughs has led to considerable groundwater flooding events in recent years beyond their normal upper seasonal boundaries following exceptional rainfall events, causing considerable damage and disruption. An extreme groundwater flooding event took place in the study catchment during the winter of 2015/2016; this represented the most extensive turlough flooding ever recorded. A number of homes and farmyards were flooded with extensive damage caused by floodwaters. The nature of groundwater flooding gives rise to lands being inundated for extended periods of time in the order of many months and during the 2015/2016 flood, many homes and farms were cut off for extended periods of time due to roads becoming impassable – see Figure 1 below. Large areas of farmland were flooded impacting on agricultural activity and causing livestock welfare concerns. Whilst the study catchment contains numerous turloughs (seasonal lakes) which ordinarily flood on an annual basis due to winter rainfall and groundwater levels, these turloughs exceeded their historic extent bounds and overflowed their natural basins in dramatic fashion often joining together to form enormous swathes of inundated lands covering many square kilometres.

Figure 1: *Flooding of roads and agricultural land with homes threatened is common in the lowlands of south Galway (Image Source: Galway Co. Co. & OPW)*

Following the flooding events of 2015/2016, the Geological Survey and the University of Dublin Trinity College collaborated on a new project to investigate flooding specifically related to groundwater and turloughs. This project, titled GWFlood, is monitoring, mapping and modelling groundwater floods to address the obvious knowledge gap that existed. Trinity College is studying one particular catchment in significant detail. The study catchment covers an area of approximately 500 km^2 in south Co. Galway and receives allogenic recharge through runoff from adjacent mountains and autogenic recharge from rainfall over the catchment. The entire catchment drains to a number of intertidal springs at Kinvara Bay via the karst limestone bedrock. During periods of sustained rainfall, the underground karst conduit system surcharges through a system of estavelles and floods low lying basins causing ephemeral lakes, known as turloughs. These turloughs provide additional storage of groundwater not available within the limestone bedrock and thus act as a form of naturally occurring management mechanism for groundwater flooding. The catchment is unique as the natural flow system has not been heavily altered by land reclamation or arterial drainage schemes and has therefore been relatively unaltered by human activities. The associated seasonal inundation cycle has led to the development of unique ecology within the normal upper and lower bounds of flooding providing a habitat for many floral and faunal species of national and international importance. Many of these areas are therefore protected within the European Natura Network.

2. KARST FLOODING MODELLING OF THE GORT LOWLANDS

2.1 Catchment Description

The Gort Lowlands karst catchment extends to c.500km^2 in south Co. Galway on the western coast of Ireland. The eastern portion of the catchment comprises largely-impermeable Devonian sandstones of the Slieve Aughty Mountains, while in the west a karstified Carboniferous limestone plain is located between the sandstone mountains, the limestones of the Burren Plateau to the south and Galway Bay to the north-west. The upland sandstones are drained via a fluvial river network whereas karstic groundwater drainage dominates the limestone lowlands and surface water features are largely sparse or absent. Groundwater and surface water flow systems within the Gort Lowlands are closely linked due to the highly-karstified nature of the limestone bedrock, with large volumes of water exchanged between the surface and subsurface throughout the catchment (Drew 2008). The exchange of water between the bedrock and the land surface largely occurs in low-lying basins known as turloughs. Many of these turloughs are important Groundwater Dependent Terrestrial Ecosystem (GWDTEs) and are protected under the EU Habitats Directive (Regan *et al.* 2007). The Gort lowland karst catchment receives allogenic recharge from the Slieve Aughty Mountains to the east via three rivers; the Owenshree to the north-east, the Bollyneendorrish to the east and the Owendalluleagh (Beagh) to the south-east. A fourth smaller river flows into the catchment from the south-west. The Clonteen River rises on the boundary between the Burren and the Gort lowlands and receives multiple spring inputs as it flows towards the centre of the catchment before sinking underground. Direct autogenic recharge also provides input to the limestone bedrock either by infiltration through the soil (where present) or as point recharge where localised concentrations of rainfall form point inflows direct to the epikarst or karstififed bedrock. Each of the three rivers flowing off the Slieve Aughty's sinks beneath the ground shortly after flowing onto the limestone from the sandstone. The Cloonteen River also sinks into the bedrock within the lowland catchment via a turlough. The water from the rivers concentrates and combines within the bedrock and ultimately outflows to the sea at Kinvara. The Owendalluleagh (Beagh) sinks and reappears twice before again sinking underground at Castletown. A number of the rivers combine underground before remerging for a short period of overland flow directly discharging to Coole Lough. It is also known that direct flow routes to the sea, bypasses at high stage and tortuous flow paths exist within the bedrock (Naughton *et al.*, 2018). This network of overland and underground rivers interacts with the land surface at multiple locations as ephemeral lakes or turloughs. The relationship between many of these turloughs and the underground/overland flow systems which exist between them has been the subject of much research (Kinahan 1865; Praeger 1932; Williams 1964). A schematic of the catchment showing the main turloughs and flood areas together with the main river inputs is given in Figure 2.

2.2 Modelling Karst Systems

Modelling karst systems is a complex and difficult task and has been the subject of continuing research globally (Hartman *et al.*, 2017). There is a broad range of different modelling approaches to simulate karst hydrology however these can be generally grouped into three categories which are differentiated by their level of complexity, input data requirements and/or the accuracy of their output. Lumped or reservoir approaches provide a conceptual model designed to simulate the aquifer outflow (usually spring discharge) as well as water level variations within the karst conduit system (the saturated bedrock zone) (Kong-A-Siou *et al.*, 2014; Hartman, 2017). These models are usually implemented by considering the karst system, which includes both the epikarst and conduit zones, and the overlying subsoil (unsaturated zone) to be represented by several reservoirs. Each of these reservoirs contain different controlling parameters and represent different inflows and outflows within the karst system. Typically, different reservoirs are used to represent zones such as the fast and slow soil infiltration, the epikarst and the conduit zones (Fleury *et al.*, 2009). This form of model is often referred to as a "lumped" model as all the physical properties of the catchment are lumped together into one model which is calibrated against the response of the entire system – usually inflow and outflow with or without some level data within the catchment. Semi-distributed models aim to address this general simplification of the catchment by acknowledging that the variability of the spatial input information and the catchment properties has significant impacts on the hydrologic responses of the system. Semi-distributed models usually sub-divide the catchment into a number of smaller sub-catchments where the distributed properties such as the land cover, soil type and precipitation are lumped into discrete zones or points which aims to more accurately represent how the catchment operates. An example of a semi-distributed model would be that presented by Harman *et al.* (2013) which considers the spatial variability of karst system properties by distribution functions. The VARKARST model takes in evapotranspiration and rainfall data across the catchment together with data regarding the soil, epikarst and karst bedrock. The soil storage takes account of the soil moisture budget allowing the seasonal changes to be accounted for – overland runoff can also be included between model elements. The catchment is compartmentalised with each compartment having its own soil, epikarst and diffuse matrix storages. Water flows from the soil storage to the epikarst storage whose output is separated between diffuse and concentrated recharge to the conduit system allowing the responses in the system to be modelled more accurately. The model was found to outperform a calibrated lumped reservoir routing model when both were applied to the same catchment (Harman *et al.*, 2013). Physically-based distributed models are capable of accounting for all of the spatial distribution of meteorological conditions (precipitation, evapotranspiration etc.) and physical parameters (e.g., soil saturation, land cover properties etc.) throughout the catchment and have the advantage of being more accurate representation of the entire catchment. In order to fully benefit from the added complexity of a fully distributed model, this approach requires a wealth of input data throughout the catchment which is often not readily available. This data requirement, together with the danger of over-parameterisation, often leads to poor model calibration. In fact, it has been reported that a lumped model generally outperforms a fully distributed model except in rigorously studied catchments (Reed *et al.*, 2004; Jeannin, 2018).

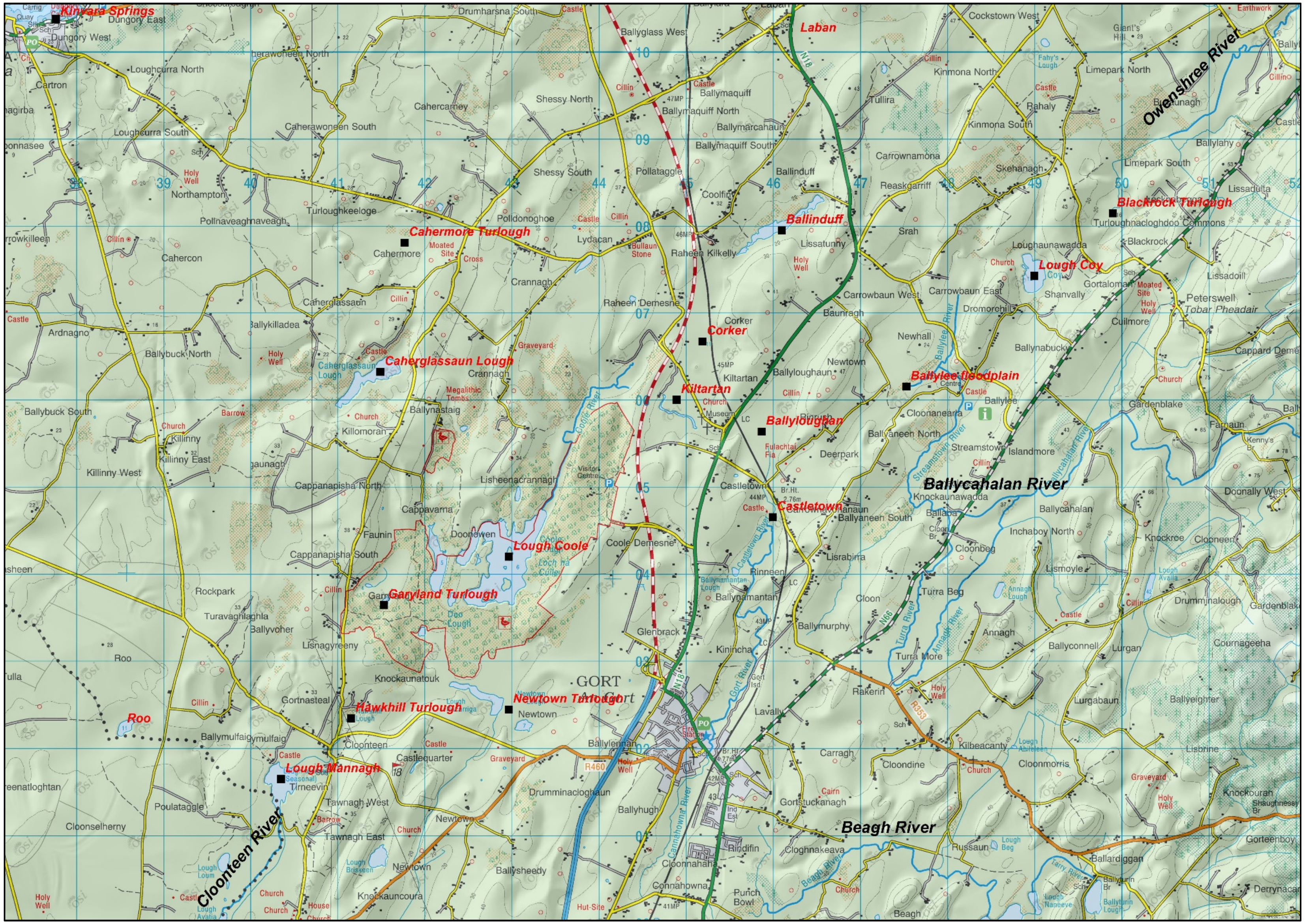


Figure 2: *Location of keys areas within the model catchment*

2.3 Pipe Network Model Development

Following the extreme flooding event of winter 1994/1995, the Gort Flood Study was commissioned by the Office of Public Works (OPW) to investigate the nature and causes of flooding in South Galway and to examine potential solutions. The project was a collaboration between Southern Water Global and Jennings & O'Donovan Partners and involved large-scale field studies of the catchment with meteorological and hydrological modelling (Southern Water Global, 1998). A simple Hydroworks model of the catchment was developed which consisted of pipes, weirs and flow controls to simulate the flooding of the rivers and turloughs within the catchment. The modelling effort, which was novel and had some relatively good results, was limited by lack of data with which to either populate or calibrate the model. The study resulted in the publication of a report, which outlined various potential flood mitigation measures, one of which was the construction of a drainage channel from the lower end of the catchment (Coole complex) to the sea at Kinvara. None of these options were considered viable and therefore were not progressed further. The final project report was issued in 1997 and made a number of recommendations on how to resolve the flooding, the majority of which were ruled out based on cost-benefit.

Since the Gort Flood Study was completed in 1997, a number of consecutive research projects undertaken in Trinity College Dublin, have involved the installation of pressure transducers to record turlough stage (water level) at a number of the turloughs in the south Co. Galway catchment (Gill *et al.*, 2013a; McCormack *et al.*, 2014). This fieldwork also involved developing rating curves on the three main rivers flowing into the lowlands as well as water chemistry analysis. Topographical surveying of the turlough basins was also carried out during dry conditions to accurately determine stage volume relationships during flooding events. Figure 3 below illustrates the filling and emptying cycle of Blackrock turlough, which is located near Gort in south Co. Galway, during the extreme flooding event of winter 2015/16. The Owenshree River flows into a swallow hole at the base of Blackrock turlough which surcharges during high flow conditions creating an ephemeral lake. During extreme events, such as what occurred in winter 2015/16, the turlough overflows at its upper basin elevation and floods adjoining lands which do not flood under normal winter conditions. Figure 3 presents daily rainfall intensities, discharge data for the River Owenshree upstream of Blackrock turlough, stage (water level) within the turlough and the flooded volume of the basin and surrounding lands.

The information presented above illustrates the complexity and unique responses of turloughs to differing and extreme rainfall events and highlights the enormity of the task of applying a model to such a system. Research projects, which took place in the mid 2000s at TCD, studied the turloughs in conjunction with the National Parks and Wildlife Service who were interested in their conservation status and thus the requirement for the development of a numerical model of the catchment. Stand-alone lumped models were developed for some individual turloughs to simulate the dynamic fluctuations in water level which could then be linked to other eco-hydrological functions (Naughton *et al.*, 2012). However, given the hydrological connectivity between turloughs in the Gort lowlands, a numerical model that could simulate their interacting water levels and outflows was required.

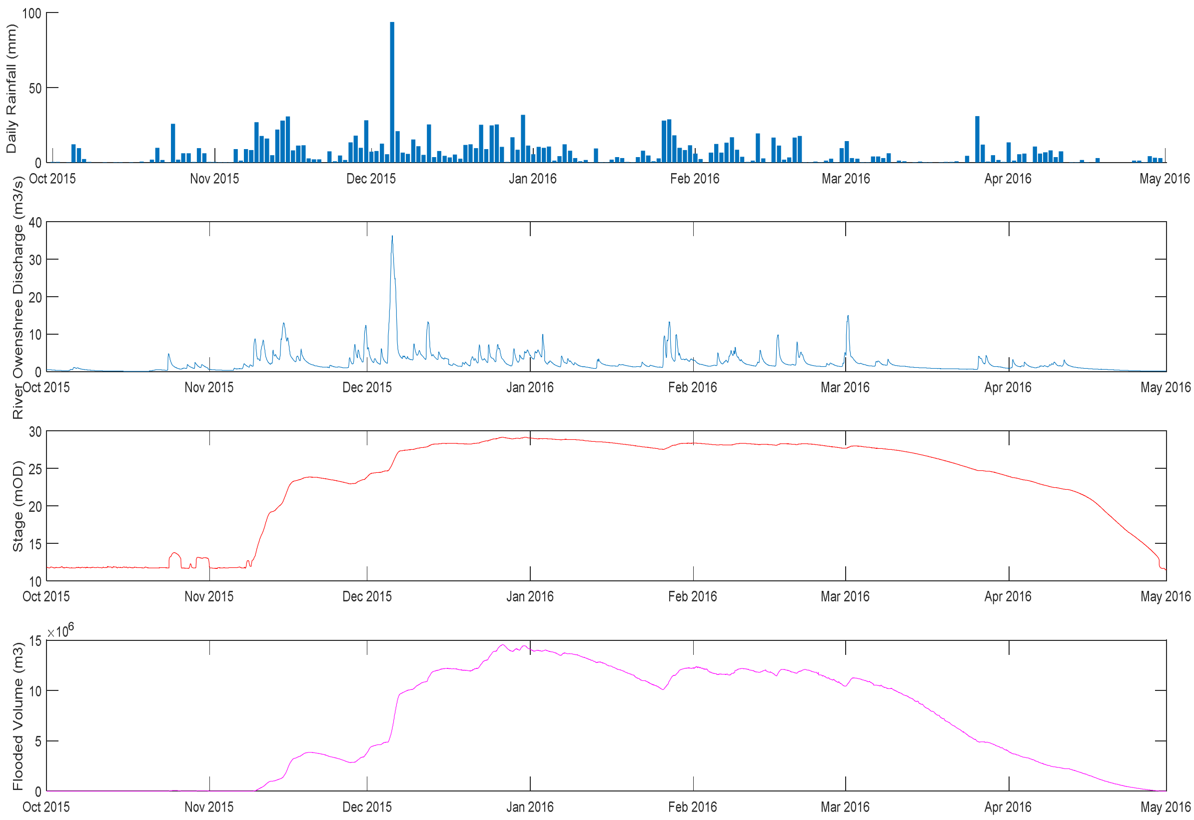


Figure 3: *Data relating to Blackrock Turlough during the 2015/16 flood event*

In order to develop such a model, a general conceptual understanding of the catchment was first required. This understanding was informed by previous extensive tracing studies carried out within the catchment as part of the Gort Flood Studies and subsequently by the GSI. Flows within the main rivers, meteorology across the catchment and water hydrochemistry, all of which has been studied and collected during various TCD research projects, allowed a deeper understanding of the system and how it operates. Time series analysis of the fluctuating turlough water levels was also undertaken. This revealed additional hydraulic characteristics regarding the nature of the catchment (Gill *et al.* 2013b) such as whether the turloughs act as surcharge tanks or not; and whether a turlough is connected to the mainline system or is located offline. Once a robust conceptual model was developed, the next task was to convert this conceptual model into a numerical model, which can accurately represent the system. Lumped models were an obvious first choice due to their relative simplicity and the modest data input requirement. The use of lumped models was however discounted. A lumped model requires the outflow from the system to be accurately quantified. As described earlier, the karst system discharges to a number of intertidal springs at Kinvara. Due to the intertidal nature of these springs, the application of traditional flow measurement techniques is not possible and more complex solutions are required. Considerable research has been carried out (Drew 2003; Einsiedl 2012; Smith and Cave 2012) using a variety of measurement approaches to estimate the system's discharge; estimates from these studies range between <1m^3/s to over 100m^3/s. Given the uncertainty involved with such discharge estimates, it was not considered prudent or viable to take such a modelling approach. A semi-distributive model of the complex karst system within the Gort Lowlands was therefore developed at TCD (Gill *et al.*, 2013a). The conceptual catchment was then represented within a complex pipe network model in the Infoworks urban storm drainage software package. Karst conduits were represented as pipes with turloughs represented as storage ponds. The boundary conditions at the catchment outfall were represented by the tide level at Kinvara. The stage-volume relationship of the turloughs was determined using the field survey data and provided the input for each pond storage area. An example of the model setup and the development from a conceptual model to a semi-distributed pipe network model is shown in Figure 4 below.

Each of the individual links within the system are characterised according to a hydraulic resistance derived from the real hydrological response from field work data – i.e. a single link could represent a single conduit or, equally, could represent an active fracture system operating under a pressure head. Balancing and controlling the system was carried out by way of throttles or flow constrictions which are known to exist upstream of turloughs and which control their outflow rates. The contribution of rainfall falling on the lowland karst limestone area that infiltrates into the epikarst and fracture network was also incorporated into the model. This was included in the model by way of two linked reservoir models. The Groundwater Infiltration Module (GIM) has been developed for Infoworks to provide a highly attenuated response to rainfall to represent the below-ground processes of infiltration through the soil into a pipe network and also the contribution from a high water table. Use was made of this module to simulate the soil and epikarst contributions to flow within the conduits. The soil storage reservoir and the ground store reservoir use a conventional reservoir routing model to control the rate and timing of inflow to the system – the conceptual setup of this model arrangement is shown in Figure 5 below. Parameters for these reservoirs were calibrated using field data, flow measurements and time series analysis.

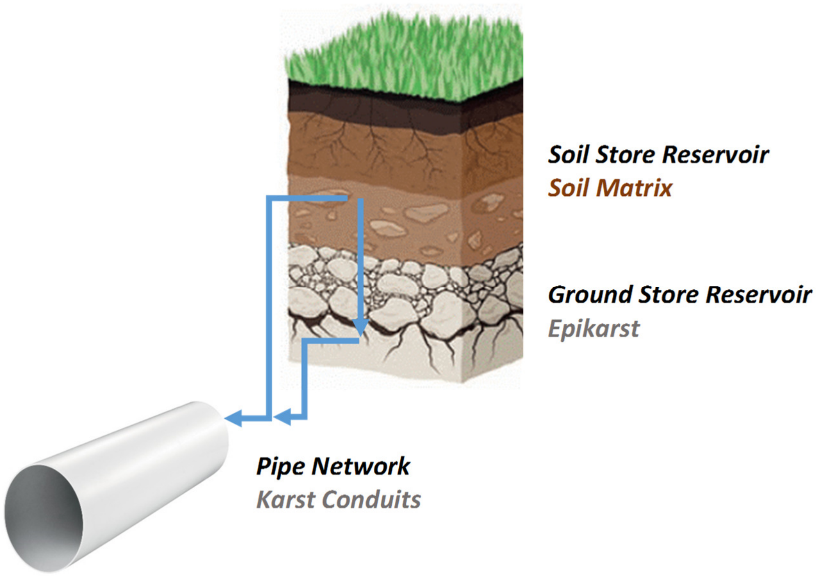
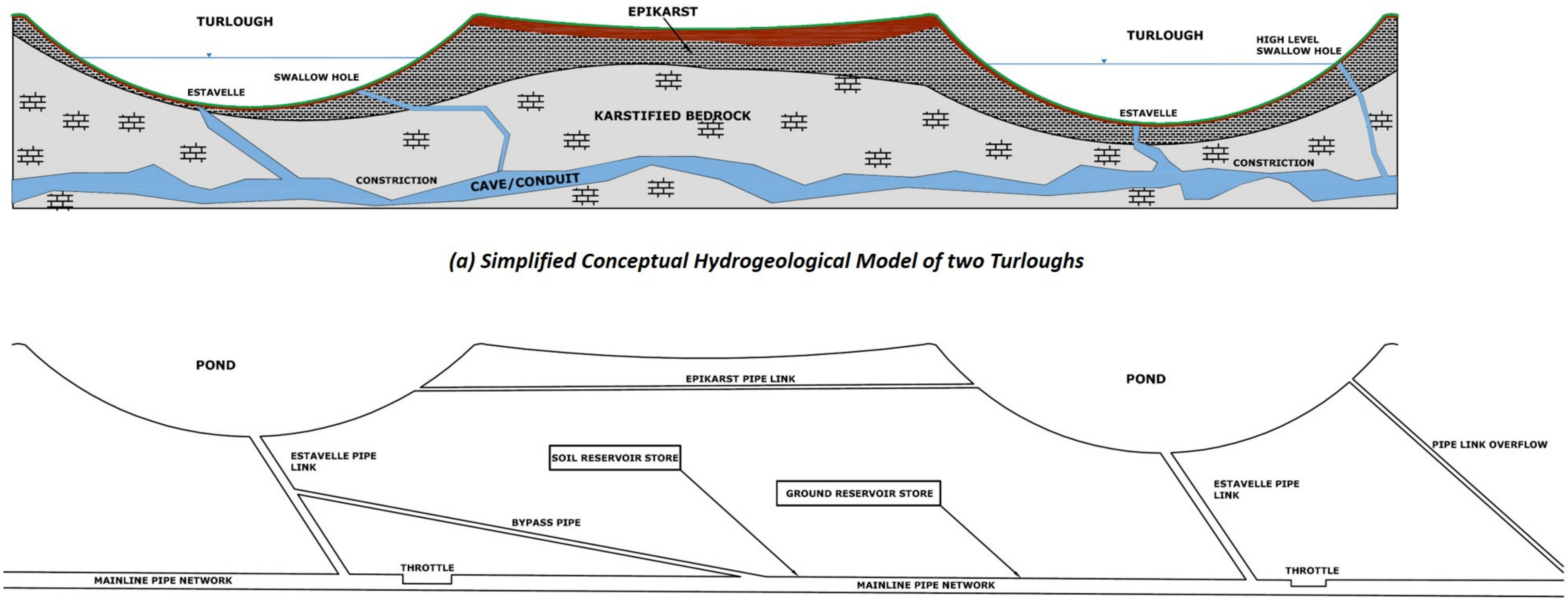


Figure 4: *Conceptual arrangement of soil and epikarst inflows to the system within the model*

The model was calibrated using historical stage data from a number of turloughs, which had been collected over an extended period and was shown to accurately simulate stage within five turloughs in the Gort lowlands (Gill *et al.*, 2013a; McCormack *et al.*, 2014).



(b) Schematic of a Pipe Network Model representing the Turloughs above

Figure 5: *Illustration of a Hydrogeological Conceptual Model represented hydraulically with a pipe network*

3. FLOOD MODELLING IN THE GORT LOWLANDS

As part of this project, the existing TCD pipe network model has been expanded from the initial five turloughs, which were included and now incorporates up to 14 turloughs and overland flooding locations as shown in Figure 2. In addition, the 1D pipe network has also been expanded to add links to a 2D mesh generated from high accuracy LiDAR data of the catchment topography allowing the flooding regime to be accurately simulated on the ground surface. The model was calibrated using a combination of historical stage data, new data collected as part of the GWFlood project since late 2016 and from digitally generated hydrographs obtained from SAR satellite imagery. Validation of the model was carried out using turlough time-series stage data and spot flood level measurements which were available for the two extreme flood events which have occurred within the catchment. An example calibration plot for the 2015/16 flooding event for Caherglassaun Lough (tidally influenced turlough) is given below in Figure 6.

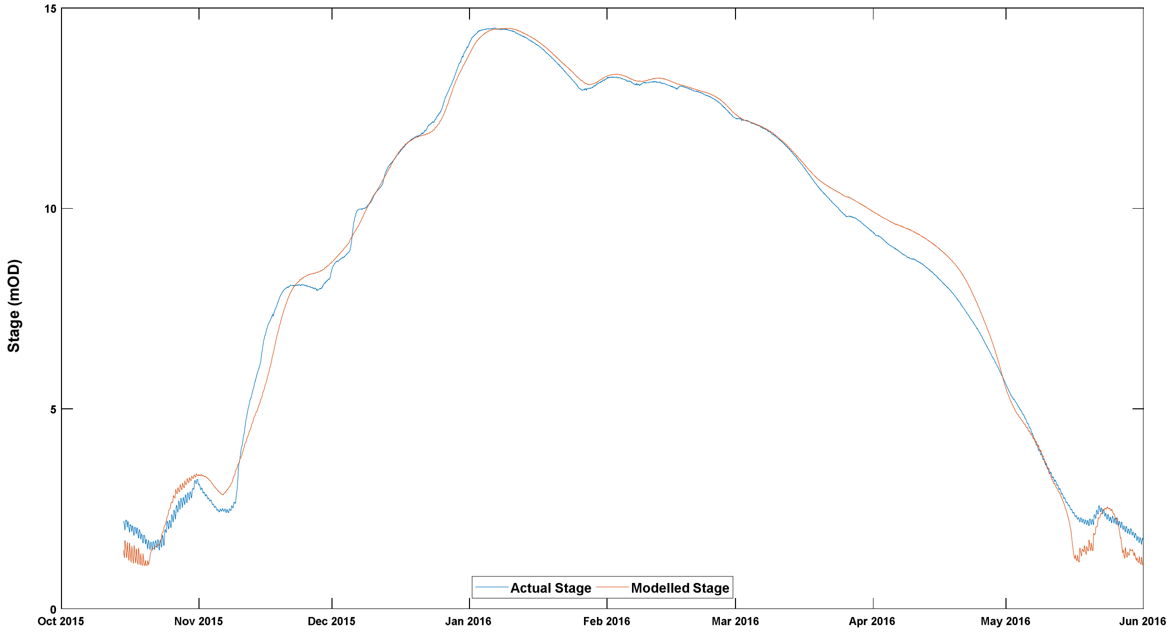


Figure 6: *Sample Model calibration for Caherglassaun Turlough (2015/16 flood event)*

It can be seen that a very good agreement between the modelled and observed stage (and correspondingly volume) has been achieved representing a Nash-Sutcliffe model efficiency coefficient of 0.991 and a volume error of <1% with a mean square error of 0.4m. Nash-Sutcliffe model efficiency coefficients for the model output at each of the turloughs has been carried out and values ranging between 0.89 and 0.99 have been achieved at all locations where temporal data were available. In addition, peak flood spot levels were available to validate flood locations where temporal data were not available.

In order to further validate the model and ensure its robustness for predictive purposes, rainfall and evapotranspiration data dating back to 1988 were obtained for the catchment and distributed using standard approaches from the literature. Rainfall runoff models using Mike NAM modelling software were developed for the river inputs and modelled river flows were generated. Historic tidal data were also obtained from the Marine Institute for Galway Bay. The model was then run for the period 1989 to 2018 and the results examined. The historic flood events of 1990 and 1994/95 were then assessed within the model using spot flood levels which had been recorded by the GSI/OPW (GSI, 1992; OPW, 1994). A plot of this validation model output for Blackrock turlough is given in Figure 7. The model successfully represented the flood events for 1990 and 1994/95 and a good agreement with reported flood levels was observed. Given that the model performed well over this time period, it is concluded that significant land use changes and/or major collapses/changes in the karst system did not occur.

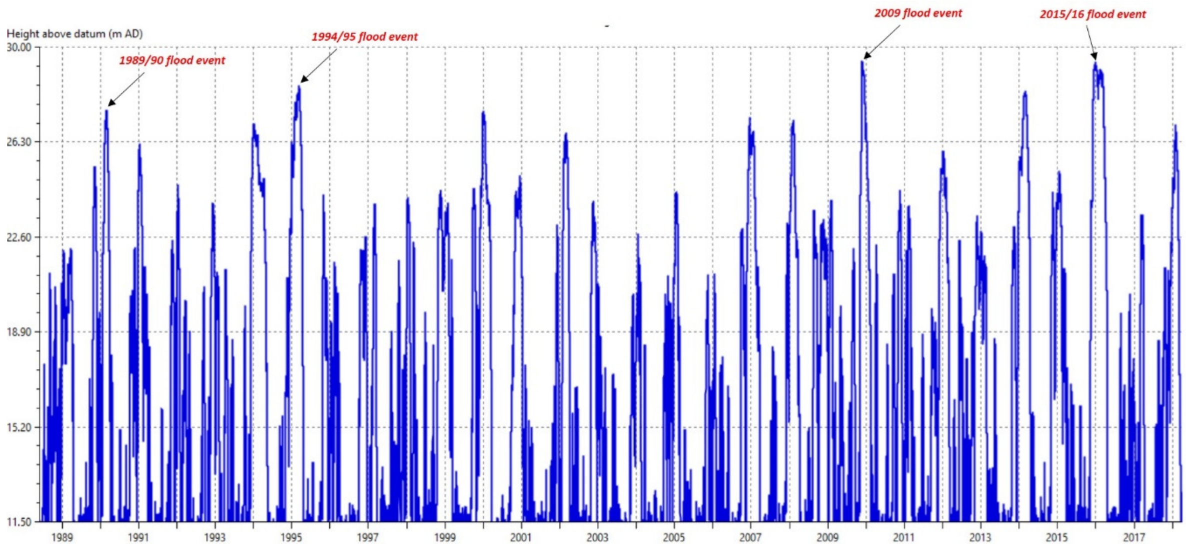


Figure 7: *Simulated Turlough Stage at Blackrock Turlough between 1988 and 2018*

The model has also been developed in a 1D/2D environment. High accuracy LiDAR data is available for the majority of the model catchment and this allowed the overland portion of the flooding to be represented by a 2D mesh. The pond storage elements were removed from the model and instead replaced with links to the mesh at locations of swallow holes or estavelles. Due to the size of the catchment, and due to the relatively small time steps required to achieve convergence and the number of mesh elements required, computation time for the 2D element is long. Calibration of the 2D model is on-going. However a relatively good agreement with the maximum flood extents from 2015/16 has to date been achieved – see Figure 8 below.

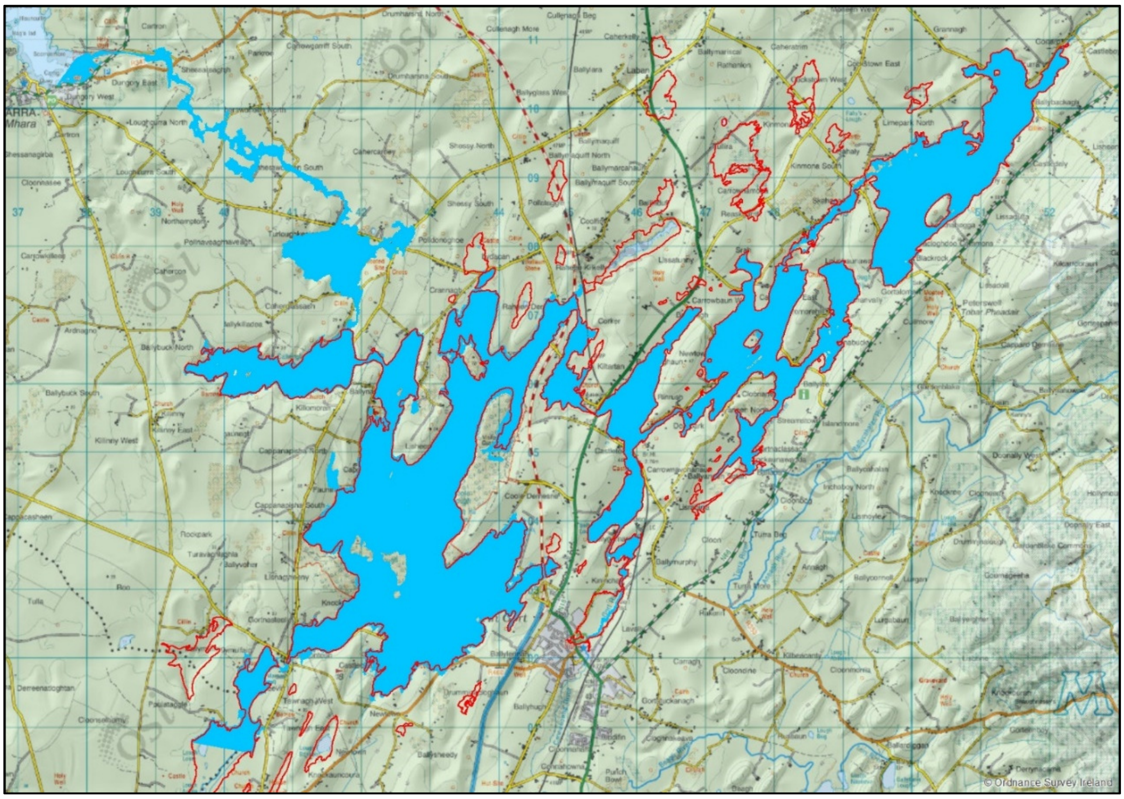


Figure 8: *Preliminary 2D model calibration (Modelled flood extents in blue; available surveyed flood extents outlined in red)*

4. PROBABALISTIC FLOOD MODELLING

In order to fully appreciate the flooding mechanisms of the turloughs and quantify the likely re-occurrence of historic flood events, it is necessary to define flood frequencies and flood return periods to levels at each flood location. The nature and extent of groundwater flooding is characterised by very different governing processes when compared to fluvial flooding and therefore the standard approaches taken in the Office of Public Works CFRAM project are not necessarily appropriate. Groundwater flooding is not characterised by single peak flood hydrographs but is an accumulation of water, which can occur over durations in excess of 30 days. A methodology for defining such flood frequencies for groundwater flooding in the Gort lowlands has been developed by TCD and the GSI. The methodology involves a stochastic weather generator (weaGETS) which was trained using historic records at Gort Derrybrien rainfall station to produce a long-term synthetic record of rainfall data for the catchment. This synthetic rainfall record, together with long-term evapotranspiration values, was then used to simulate river discharges using rainfall runoff models. The pipe network model was then run for the full dataset and flood frequency analysis was performed for each turlough and flood area to determine predictive flood levels (return periods).

TCD are also collaborating with the Irish Centre for High End Computing (ICHEC); and Met Éireann, are also progressing a complex climate change assessment of the catchment. An ensemble of downscaled CMIP5 RCM (Coupled Model Intercomparison Project Phase-5 Regional Climate Model) simulations is currently running for the period 1975-2100 at Met Éireann. Projections for the future Irish climate are being modelled by downscaling the UK Met Office's Hadley Centre Global Environment Model (version 2), Earth System configuration (HadGEM2-ES) Global Climate Model (GCM), the EC-Earth consortium GCM, the Max Planck Institute for Meteorology Earth System Model (MPI-ESM-LR), and the International Centre for Earth Simulation Model for Interdisciplinary Research on Climate (version 5) (MIROC5). To account for the uncertainty arising from the estimation future global emission of greenhouse gases, two IPCC Representative Concentration Pathways (4.5 and 8.5) emission scenarios were used to simulate the future climate of Ireland (Nolan, 2015). Rainfall and Evapotranspiration (ET) data for the catchment in future climate change scenarios will be used to model river inflows to the catchment. The future rainfall and ET datasets will then be used together with these simulated future river flows to model the flood levels and durations of turloughs across the catchment.

5. MODEL APPLICATION

The advantage to using a semi-distributed pipe network model (a physical model) is that physical changes within the catchment (such as the inclusion of flood defences) can be incorporated into the model and it can then be used to simulate the predicted impacts of same within the catchment. Changes to land use within the catchment can also be investigated and assessed as to their likely impact. The calibrated model was recently used to assess the implications of changing land uses on the Slieve Augthy Mountains which provide a significant proportion of inflow to the catchment. It has been suggested by many interested parties that land use changes in the Slieve Aughty Mountains may be contributing and/or exacerbating the flooding which occurs in the karst lowlands. Intensive forestry and the associated drainage works have been suggested as a potential cause, or contributing factor, to more recent flood events with increases in the peak storm hydrographs hypothesised on the rivers flowing down from the Slieve Aughty Mountains. The construction of the Derrybrien windfarm has also been suggested as a potential factor exacerbating flooding in the lowlands. Previous studies have shown that an increase of up to 18% in runoff can occur following afforestation of peaty uplands with conifers (Robinson *et al.*, 1998). More extreme flood hydrographs are also observed at similar catchments following the inclusion of forestry drainage. The flood hydrographs for the three rivers flowing off the mountains were therefore modified using the values reported from in the literature to simulate how the catchment would have responded to the flood of 2009 had no forestry been present (or if forestry drainage were similar to the previous land use). A number of scenarios were simulated and it was found that, based on values reported for similar catchments, flooding of a similar extent and duration occurred regardless of the reduced runoff volumes or peak intensities. This is principally due to the inability of the karst system to accept greater inflows once the system has surcharged.

The largest river which flows off the Slieve Aughty mountains, the Owendalluleagh (Beagh), flows through Lough Cutra (a permanent lake) before entering the lowlands. The Gort Flood Study report of 1998 suggested the damming of the Owendalluleagh (Beagh) upstream of Lough Cutra and impounding water there during extreme flood events by way of bunds. The model was used to assess the impacts of such a flood alleviation measure and the level of storage required versus the potential reduction in peak flood levels within the catchment. A dam with a maximum discharge rate of $10m^3/s$ was added to the model upstream of Lough Cutra (which was assumed to have an infinite storage capacity) and the 2009 flood event was simulated. The model predicted that c.33.5 x 10^6m^3 ($33.57Mm^3$) of additional water was stored at Lough Cutra; this flood water was then released at a maximum discharge rate of $10m^3/s$ thereafter. The impacts of the inclusion of the dam was significant with peak levels at Coole Lough (the largest turlough in the system) reduced by c.1.5m with a slower recession from the peak flood level. Similarly, peak flood levels at the majority of the lower turloughs and floodplains were also reduced with the effects more muted at the top end of the catchment. A dam on Lough Cutra has an impact on flooding in the lowlands as the water is held back in the lake for a period long enough for the turloughs to drain sufficiently before accepting further water. The practicality of constructing such a dam and flood impoundment area were not considered but the exercise demonstrates the usefulness of such a model when designing flood alleviation schemes. The project will continue to examine the impacts of more practical and cost-effective flood solutions in the comings months in collaboration with the OPW, Galway County Council and their consultant engineers.

6. CONCLUSION

Groundwater flooding in turlough systems poses a significant risk to property and agriculture causing widespread cost and disruption for long periods when it occurs. The more frequent and extreme flood events that have occurred in recent years have highlighted the need to improve our ability to understand and quantify the frequency and mechanisms by which this flooding occurs.

Understanding, and indeed modelling, groundwater flooding is a difficult and complex task that requires a novel solution. Trinity College Dublin is in the process of developing new and novel approaches to modelling groundwater flooding that occurs in turloughs with a view to providing essential data to inform decisions regarding groundwater flood mitigation and prevention.

7. ACKNOWLEDGEMENTS

This work was supported by Trinity College Dublin – The University of Dublin and Geological Survey of Ireland. The authors would also like to thank the OPW, EPA, NPWS, Marine Institute, Met Eireann, Galway County Council and local landowners living within the catchment for their on-going assistance and support.

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