Groundwater flood hazards and mechanisms in lowland karst terrains

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Abstract: The spatial and temporal complexities of flooding in karst terrains pose unique challenges in flood risk management. Lowland karst landscapes can be particularly susceptible to groundwater flooding due to a combination of low aquifer storage, high diffusivity and limited or absent surface drainage. Numerous notable groundwater flood events have been recorded in the Republic of Ireland throughout the twentieth century, but flooding during the winters of 2009 and 2015 was the most severe on record, causing widespread and prolonged disruption and damage to property and infrastructure. Effective flood risk management requires an understanding of the recharge, storage and transport mechanisms governing water movement across the landscape during flood conditions. Using information gathered from recent events, the main hydrological and geomorphological factors influencing flooding in these complex lowland karst groundwater systems are elucidated. Observed flood mechanisms included backwater flooding of sinks, high water levels in ephemeral flooded basins (turloughs), overtopping of depressions, and discharges from springs and resurgences. This paper addresses the need to improve our understanding of groundwater flooding in karst terrains to ensure efficient flood prevention and mitigation in the future, and thus helps to achieve the aims of the European Union Floods Directive.

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Karst landscapes present a unique set of environmental and engineering challenges to planners, stakeholders and the scientific community. Geohazards such as subsidence, sinkholes, landslides, flooding and water contamination are common in karst environments (Santo et al. 2007; Zhou 2007; Maréchal et al. 2008; Worthington et al. 2012; Gutiérrez et al. 2014; Martinotti et al. 2017). Flooding and flood risk management is a major challenge facing society in the coming decades, especially in the light of the increased frequency of extreme weather events as a result of climate change (Intergovernmental Panel on Climate Change 2014). Effective flood risk management requires an understanding of the recharge, storage and transport mechanisms in operation during flood conditions. In the context of groundwater flooding within karst systems, the heterogeneous and anisotropic nature of water-carrying fractures and conduits beneath the surface lead to obvious problems in developing such an understanding (Field 1993).

Karst terrains are uniquely susceptible to flooding from groundwater sources due to a combination of the low storage and high diffusivity characteristics of these aquifers (Parise et al. 2015). Water levels within karst groundwater systems can rise dramatically during periods of intense or prolonged rainfall. As the subsurface storage and drainage reaches capacity, the rising water table can reach the topographic surface and produce floods (Gutiérrez et al. 2014; Naughton et al. 2017). However, unlike linear flood features such as river channels or coastlines, the manifestation of groundwater flooding may be discontinuous and determined by the spatially variable hydrodynamic properties and responses within the karst system. The surface expression of groundwater flooding may only occur during extreme weather events and at relatively long recurrence intervals. Thus the flood frequencies traditionally used in flood risk assessment (such as 10 or 1% annual exceedance probability) may be undefinable. These inherent difficulties are explicitly acknowledged within the European Union Floods Directive 2007/60/EC, whereby Member States are permitted to limit groundwater flood hazard maps to extreme event scenarios only.

Groundwater flooding has not traditionally been recognized as posing a significant risk and so remains relatively less well understood than other forms of flooding (Bonacci et al. 2006; Morris...
et al. 2007). Consequently, investigations into the contribution of karst hydrology to surface flooding are still in their infancy (Gutiérrez et al. 2014). This has begun to change in the last decade or so, driven, in part, by the introduction of the European Union Floods Directive and its requirement to consider all forms of flooding, including groundwater, but primarily due to a series of groundwater-related flood events across Europe – in France (Pinault et al. 2005; Maréchal et al. 2008), Spain (Lopez-Chicano et al. 2002), the UK (Hughes et al. 2011; Morris et al. 2015), Croatia (Bonacci et al. 2006) and Italy (Parise 2003). Studies of polje hydrology and flooding are perhaps the best described in the literature.

In the Republic of Ireland, the last decade has seen the worst groundwater flooding in living memory. The dramatic floods during the winters of 2009 and 2015 caused widespread damage and disruption to communities across the country, particularly in the extensive karstic limestone lowlands on the western seaboard (Naughton et al. 2017). This paper presents a detailed example of the phenomenon of groundwater flooding in the lowland karst terrains of western Ireland. Using examples and insights gained during the recent unprecedented flood events, we describe the main hydrological and geomorphological characteristics influencing flooding in these complex lowland karst groundwater systems.

**Background and geological context**

Limestone accounts for >40% (30 000 km²) of the surface or near-surface outcrop in the Republic of Ireland, making it the most prevalent bedrock type and primary regionally important aquifer lithology in the country (Simms 2004; Drew 2008). The main Irish limestones were formed during the Early Carboniferous or Dinantian (Drew et al. 1996) when a marine transgression in the Tournaisian period inundated much of the Old Red Sandstone continent and provided the depositional environment necessary for limestone formation (Guion et al. 2000; Sevastopulo & Wyse Jackson 2009). The telegenetic origin of Irish limestones has resulted in little primary (matrix) porosity; instead, modern groundwater circulation is dominated by secondary (joints, fractures and bedding planes) and tertiary (solutionally widened) porosity. Irish limestones have undergone karstification many times since their formation, with the most significant period being the Tertiary (65–2 Ma) (Williams 1970; Drew 1990). Karst features have been documented in >80% of the limestone outcrop, indicating that karstification has occurred across most, if not all, of the limestone formations in the country (Drew et al. 1996). More recent dissolution processes during the Holocene (10 ka to present) has also resulted in the development of a weathered epikarst zone near the bedrock surface, as well as active karst features, such as stream caves in the Burren (White 1988; Drew & Jones 2000; Drew 2008).

The degree of karstification varies significantly across the country due to variabilities in the bedrock purity, fracturing and landscape history. Karst features are sparse or absent across much of the central and eastern limestones, where normal fluvial drainage systems have developed with little interaction with the underlying karst aquifer (Coxon 1986). By contrast, karst groundwater flow systems dominate on the relatively pure, well-bedded lowland limestones in the west of the country (Fig. 1). These lowlands experience a western maritime climate with a long-term average annual rainfall (1981–2010) of c. 1100 mm (Walsh 2012). Recharge is principally autogenic in the form of direct (diffuse) and local point recharge; significant allogetic recharge is relatively uncommon (Drew 2008). One notable exception to this is the Gort Lowland catchment in south Galway, which receives the majority of catchment recharge from the adjoining sandstone uplands (Gill et al. 2013; McCormack et al. 2014).

Over 90% of Irish karst occurs in a low-lying or lowland setting, typically <100 m above sea-level (Drew 2008). A distinguishing feature of Irish lowland karst terrains is the relatively shallow depth of the vadose zone, wherein the phreatic surface remains close to or at the surface throughout the year. There is widespread water circulation between the surface and groundwater flow systems in this hydrogeological setting, with frequent reversals of the hydraulic gradients. The shallow depth to groundwater limits the buffering effect of aquifer storage during recharge events. The lack of vadose zone storage is mitigated by the presence of a well-developed epikarst, where significant weathering, fracturing and dissolution of the near-surface bedrock provides additional storage. Nonetheless, ephemeral surface flooding from groundwater sources is a prevalent feature of lowland karst terrains in Ireland.

During periods of high rainfall, excess recharge that cannot be accommodated by the subterranean network of water-bearing fractures and conduits is temporarily stored in ephemeral, geographically isolated water bodies known as turloughs. Turloughs vary in size from ≤1 ha to >250 ha and more than 400 active turloughs have been documented (Sheeby Skellington & Gormally 2007). Turloughs are usually located along lines of concentrated flow within an aquifer and thus play a key part in lowland karst hydrology (Sheeby Skellington et al. 2006); they act as temporary storage for local and regional recharge in a role akin to that of temporary bank and floodplain storage in fluvial systems (Naughton...
et al. 2017). Turlough flooding thus bears many similarities to that which occurs within poljes in karst, in that both act as a subsystem of surface and groundwater flow through the karst groundwater flow system (Bonacci 2013). In fact, turloughs have been considered to be a subtype of the polje landform. Both karst depressions display complex hydrological and hydrogeological characteristics, such as periodic inundation, temporary springs, lacustrine sediment deposition, swallow holes and estevelles. As with turloughs, the flooding within poljes can be severe and pose a significant flood hazard to surrounding properties and infrastructure (Mijatovic 1988; Kovacic & Ravbar 2010).

During typical winter rainfall levels, flooding is confined within the basin and acts as an environmental supporting condition for the wetland floral and faunal species that have colonized the turlough habitat (Sheehy Skeffington et al. 2006; Moran et al. 2008a; Porst et al. 2012). During extreme and/or prolonged rainfall, floodwaters within the basins can reach extreme levels and cause widespread damage and disruption to the surrounding areas. It is in this context that turloughs represent the principal form of recurrent, extensive groundwater flooding in Ireland. Historically, groundwater flooding has been centred on the karst limestone plains of the western lowlands, principally in counties Roscommon, Mayo, Galway and Clare (Fig. 1). The last decade has seen the worst groundwater flooding that the western limestone lowlands of Ireland have experienced in living memory.

Groundwater flood events of 2009–10 and 2015–16

The winters of 2009–10 and 2015–16 were exceptionally wet seasons across the Republic of Ireland. Although both winters represent extreme meteorological events, they differed in the intensity and duration over which rainfall persisted. The heavy rainfall events of 2009 were caused by a series of deep, fast-moving Atlantic depressions crossing
the country during November. Over twice the long-term average amounts of rainfall were recorded at stations across Ireland, making November 2009 the wettest on record (Walsh 2010; McCarthy et al. 2016). By contrast, the winter of 2015–16 saw more persistent wet weather. A succession of storm fronts moved across Ireland from November to February, bringing with them exceptional rainfall accumulations across much of the country (McCarthy et al. 2016). Between December and February, a total of >600 mm (189% of the long-term average) fell across the island of Ireland, making it the wettest winter on record in a rainfall time series stretching back to 1850 (McCarthy et al. 2016; Noone et al. 2016). December 2015 was also the wettest of any month on record in Ireland, with five stations exceeding the previous Irish record for the highest monthly rainfall total (McCarthy et al. 2016).

The unprecedented rainfall events during the winters of 2009–10 and 2015–16 caused widespread damage and disruption to residential houses, businesses, infrastructure and agriculture across the region. The sustained nature of the flooding, lasting for more than three months in some cases, caused prolonged hardship to rural communities, who struggled to prevent the inundation of homes and workplaces amid unparalleled disruption to transport networks. The flooding of large tracts of agricultural land severely affected agricultural activity and posed a serious welfare risk to livestock, while anoxic soil conditions due to prolonged submergence damaged hundreds of hectares of valuable pasture land. An idea of the scale of flooding is given in Figure 2, which shows the extent of floods for south Co. Galway during the winter of 2015–16 derived from field and satellite synthetic aperture radar measurements. This region is effectively devoid of permanent surface water. The flooded extents shown, encompassing an area >38 km², are primarily associated with flooding of the karstic groundwater system. Further widespread flooding was also reported in counties Roscommon and Mayo, with more localized events in Clare, Longford and Westmeath.

Fig. 2. Groundwater flood extent map for 2015–16 flooding in the Gort Lowlands, Co. Galway, Ireland (derived from field measurements and SAR imagery courtesy of Copernicus Emergency Management Service).
Groundwater flood response

Of these two exceptional winters, it was 2015–16 which generally saw the highest groundwater levels and most widespread flooding. Although some of the difference can be accounted for by regional variations in rainfall, the duration (or persistence) of heavy rainfall was the primary cause. The crucial durations governing groundwater flooding can vary dramatically depending on the hydraulic properties and structure of the aquifer system, with response times ranging from minutes and hours up to multi-annual timescales (Maréchal et al. 2008; De Waele et al. 2010; Hughes et al. 2011). In the case of lowland karst groundwater flow systems in Ireland, surface flooding is strongly related to the cumulative rainfall typically measured in weeks to months (Moran et al. 2008b; Naughton et al. 2012). Figure 3 shows the maximum rainfall depths for a range of durations from the Irish Meteorological Service (Met Eireann) rainfall station in Gort, south Galway. Both winters showed rainfall totals significantly above the median (1981–2010) for the area. For shorter durations (<40 days), the rainfall totals in 2009 exceeded those experienced in 2015, whereas for higher durations this reversed, with the rainfall totals in 2015 significantly exceeding those of 2009. This greater flooding experienced during 2015–16 is an indication that the crucial rainfall durations influencing the magnitude of groundwater floods in Irish karst systems lies in this range.

The relationship between antecedent rainfall and flood magnitude varies significantly within and between systems, reflecting heterogeneities in the extent of karstification, hydraulic connectivity and aquifer storage. This variability gives rise to a spectrum of flooding regimes within turloughs, ranging from short duration flooding in basins with a rapid response to rainfall events, to long duration flooding in response to longer term precipitation patterns (Naughton et al. 2012).

An example of the variability in water level response during flood conditions is demonstrated in Figure 4, which shows normalized water level hydrographs (relative to their peak level) for three turloughs in south Co. Galway during the 2009 flood event. Substantial differences are evident in hydrograph shape and the timing of peak flood levels, despite comparable inputs of rainfall. The flood maximum in Blackrock turlough occurred on 26 November 2009, about three weeks after the onset of flooding within the basin. Over this period, the floodwaters reached depths of up to 18 m, representing a flood volume of >15.6 × 10⁶ m³, which included a 2.9 × 10⁶ m³ increase over a single day. Blackrock turlough has an extensive allogenic upland catchment with the capacity to rapidly deliver large amounts of recharge to the turlough, which is, in turn, drained by a large conduit network (McCormack et al. 2016). By contrast, the nearby Caranavoodaun and Termon turloughs have more localized autogenic catchments. Caranavoodaun turlough showed a damped response compared with Blackrock, with peak levels lagging by about eight days and showing a relatively prolonged recession. Termon South turlough did not peak until much later than the other two turloughs.

![Figure 3](https://example.com/figure3.png)

**Fig. 3.** Maximum rainfall depths recorded at the Gort (Derrybrien) rainfall station, Co. Galway for winter 2009–10 and 2015–16.
later in the flooding season, on 6 January 2010. The heavy rainfall of November 2009 contributed significantly to the stored floodwaters within Termon, but the slow drainage characteristics of the underlying groundwater flow system meant that peak levels occurred much later in the season after further rainfall. The flood maximum in Termon turlough is thus a function of a rainfall duration measured in months rather than the weeks of Blackrock turlough.

**Groundwater flooding mechanisms**

In response to the flooding in 2009 and 2015, we carried out a series of studies for key locations identified by the Office of Public Works and local authorities as potentially affected by groundwater flooding. The objective was to assess the extent, nature and mechanisms of flooding, whether a significant flood risk existed and whether groundwater was the key contributor to that risk. Consistent long-term data on groundwater flooding in Ireland do not exist and information was therefore derived from diverse sources, including field measurements, hydrometric data, aerial photography, satellite imagery, historical land maps, technical reports, local authority road closure notices, local accounts and media sources. What became apparent during the study was that although the primary form of extensive, recurrent groundwater flooding in Ireland originates in turloughs, a range of mechanisms beyond simple turlough flooding play a key part during extreme groundwater flood events.

From experience in the Chalk aquifers of southern England, Robins & Finch (2012) proposed two distinct types of groundwater flood event: groundwater flooding and groundwater-induced flooding. The former is considered as a true groundwater flood in which the water table rises above the ground elevation, whereas a groundwater-induced flood occurs when intense groundwater discharge via springs and highly permeable shallow horizons discharges to the surface water, causing overbank flooding (Robins & Finch 2012). A similar division is proposed here for lowland karst groundwater systems, wherein flood mechanisms can be broadly divided into those where the damage mechanism is primarily due to either hydrostatic action or hydrodynamic action. The principal mechanisms identified...
are given in Table 1 and Figure 5 and represent the type examples of how groundwater flooding manifests in Irish lowland karst catchments. The main damage mechanism in turlough and backwater flooding of sinks is by hydrostatic action, whereby elevated water levels with low or negligible water velocities pose a risk to surrounding receptors. Mechanisms where hydrodynamic action (flowing water) posed a risk included ephemeral overland flow due to overtopping of flooded depressions, and excess discharge from permanent/transient springs and resurgences.

**Turlough flooding**

Turloughs represent the principal form of recurrent, extensive groundwater flooding in Ireland. Dozens of examples of flooding around turlough basins were identified across the western lowlands (e.g. Fig. 2). Although the numbers of receptors affected at any one site were relatively low, cumulatively turlough flooding caused extensive damage and disruption to communities across the region. For example, Rahasane turlough, in the Dunkellin River catchment, Co. Galway, flooded 12 houses along its

**Table 1. Groundwater flooding mechanisms in lowland karst groundwater systems in Ireland**

| Type                        | Damage         | Description                                                                 |
|-----------------------------|----------------|----------------------------------------------------------------------------|
| Turlough flooding           | Hydrostatic    | Turlough floodwaters rise to extreme levels and pose a flood risk to the surrounding area |
| Backwater flooding          | Hydrostatic    | Point recharge (sinking streams/rivers) exceeds the groundwater drainage capacity, causing inundation of the sink itself and backwater flooding upstream |
| Overtopping of sinks/basins | Hydrodynamic   | Ephemeral overland flow due to overtopping of flooded depressions           |
| Discharge from springs and resurgences | Hydrodynamic | (a) Groundwater springs and risings at the periphery of upland areas exceed normal discharge levels, causing flooding around and downstream of the resurgence (b) Shallow lateral flow paths are activated within the epikarst by high groundwater levels, triggering ephemeral springs and flooding of adjacent depressions |

![Fig. 5. Groundwater flood mechanisms in lowland karst groundwater flow systems: (a) turlough/backwater flooding of sinks; (b) overtopping of basins and sinks; (c) discharge from spring and resurgences at the periphery of upland areas; and (d) lateral flow through shallow epikarst pathways.](image-url)
banks during the November 2009 event. Flooding at Labane turlough, Co. Galway, forced the closure of the N18 road between Galway City and Limerick City for more than two months. Further north at Lough Funshinagh, Co. Roscommon, floodwaters in 2015–16 were the highest in living memory, covering an area of 4.6 km² with a peak volume of >16 × 10⁸ m³. Lough Funshinagh was notable due to the length of time the floodwaters persisted, with water levels falling at a rate of only a few centimetres per week. Flood levels remained high throughout 2016 and were still above the previous record flood (from 2009 to 2010) a full six months after the peak.

The nature of flooding, in terms of timing, extent and duration, varied substantially, both locally and regionally, in line with the spectrum of flooding regimes and modus operandi characteristic of turloughs (Naughton et al. 2012). This may in some part be due to their polygenetic origins and the complex landscape history of Irish limestones. Turloughs were originally considered as hollows in glacial drift with underlying karst drainage systems (Williams 1964). However, Drew (1973) asserted that turloughs invariably lie in bedrock hollows and were solutional features requiring a far longer period to develop than has passed since the last glaciation. Coxon & Coxon (1994) suggested that turloughs are polygenetic, with glacial deposition influencing their morphology, but solutional rather than glacial processes being the determining factor in turlough formation. The lines of high permeability associated with turloughs may thus represent the re-use of remnants of karst drainage systems created during Tertiary dissolution, but subsequently partially blocked by glacial drift, rather than post-glacial dissolution pathways. Coxon & Drew (1986) suggested three models to explain turlough origin and the presence of the high permeability zones required for turlough formation: (1) glacial hollows with flow paths developed post-glacially; (2) glacial hollows that developed along the line of existing pre-glacial flow routes; and (3) pre-glacial karst features with associated flow paths modified by glaciation.

The hydrological budget of turloughs can be described using two general conceptual models: through-flow systems and surcharged tank systems (Naughton et al. 2012). Rainfall onto, and evaporation from, the water body is common across all models, as well as surface runoff from the surrounding slopes. Surface evaporation is generally of minor importance to the water budget due to the seasonality of turlough flooding because it typically occurs during the winter months. Direct precipitation and runoff can be significant, particularly in shallow, flat basins, but under flood conditions groundwater flow is the dominant hydrological process.

In through-flow systems the recharge and discharge processes work in partial isolation, with no direct transfer of water between them without first passing through the main water body. The turlough basin effectively acts as a sink, receiving recharge from the surrounding vadose zone, shallow groundwater systems and/or point recharge. In the case of a purely distributed through-flow system, drainage occurs via a distributed network of shallow fractures and conduits (Fig. 6a). Through-flow systems can also consist of point recharge and discharge (Fig. 6b), but groundwater flow within the system elements is unidirectional. In a surcharged tank system (Fig. 6c), the main recharge and discharge processes do not occur simultaneously. Instead, the water budget is controlled by a bidirectional flow system located at or near the turlough base, with the turlough acting as overflow storage for the underlying conduit network. Under this scenario there is no significant discharge from the turlough during filling periods. During recession periods recharge is still derived from the local (proximal) shallow groundwater systems, but not from the distal catchment (Naughton et al. 2012).

Understanding the nature of a turlough’s hydrological budget is crucial if active flood management measures are to deliver the intended outcomes. For example, the construction of surface drainage is often the first alleviation option considered after a flood event. A key element of drainage design is an estimate of the required channel conveyance capacity. In the case of a through-flow system, a reasonable basis for such a calculation would be the net volume changes within the basin during a representative flood season. However, this is not the case for a surcharged tank system. Artificially lowering the hydraulic head would increase the gradient into the basin, as the water budget is controlled by the head difference between the turlough and the underlying groundwater system. The extra conveyance capacity provided by the channel would thus be at least partially offset against increased recharge from the distal catchment. Although the effective catchment area required to provide sufficient recharge to flood a turlough basin may be relatively modest if operating as a through-flow system, of the order of a few square kilometres, the catchment from which floodwaters can potentially be derived can be orders of magnitude greater in surcharge tank systems. In this case, the capacity of the drain/culvert may need to be significantly greater than that in a through-flow turlough of comparable size.

The excavation and clearance of swallow holes is often cited as a potential solution to turlough flooding. Although this may improve drainage in some circumstances, the drainage rate is often not limited by localized constrictions at the inlet, but by the capacity of the underlying groundwater flow system. In the case of surcharged tank systems, any surface modification of the estevelle is unlikely to reduce
flooding because it serves as both the entry and exit points for floodwaters. In through-flow systems the rate of drainage is dependent on the flow capacity and the relative hydraulic head within the turlough and receiving groundwater system. If this gradient is sufficiently small, as is often the case during flood conditions, outflow may cease altogether and so any perceived improvement in drainage due to swallow hole enlargement is unlikely to improve the situation. Moreover, the role of turloughs as flood attenuation devices within lowland karst systems means that the reduction of flood risk in one turlough is likely to be at the expense of raising it in another, so a solid understanding of both site and catchment hydrodynamics is key.

**Backwater flooding of sinks**

Backwater flooding occurs when excess point recharge (sinking streams or rivers) causes the
inundation of dolines or sinks capable of accommodating recharge under normal conditions (Fig. 5a). This mode is analogous to the recharge-related sinkhole flooding described by Zhou (2007), whereby flooding occurs when the capacity of the sinkhole is not sufficient to transfer storm water runoff into the subsurface. The damage mechanism in backwater flooding is principally hydrostatic, but such cases clearly have a strong fluvial component given their dependence on the discharge of the influent surface water. Backwater flooding is common across the Irish karst lowlands, but in the clear majority of cases it is related to small autogenic streams with low baseflow discharges and so does not pose a significant flood risk. Historically, large-scale backwater flooding in karst areas would have been relatively common. However, many areas formerly characterized by internal drainage have been systematically modified by arterial drainage schemes built during the late nineteenth and early twentieth centuries (Drew & Coxon 1988). For example, the 1000 km$^2$ Clare River catchment in north Co. Galway originally discharged underground via a series of large sinks, turloughs and springs. Subsequent construction and channelization of the Clare River altered the natural karstic groundwater system and it is surface water, rather than groundwater, that is now the controlling factor in present day flooding.

One catchment where the karst system has remained effectively unmodified is in the Gort Lowlands, south Co. Galway, and here backwater flooding persists as a significant flood risk. The 500 km$^2$ catchment is divided into sandstone uplands to the east and a lowland limestone plain to the west. Backwater flooding occurs where point allogenic recharge from the sandstone uplands, in the form of three rivers, discharges onto the limestone lowlands and sinks underground. The mean flows in the rivers range between 1.2 and 3 m$^3$ s$^{-1}$, but discharges can reach $>40$ m$^3$ s$^{-1}$ during flood conditions, causing widespread flooding upstream and inundating hundreds of hectares in the process (McCormack & Naughton 2016). Backwater flooding also occurs on the limestone plain due to the intermittent rising and sinking of discharges from the well-developed conduit network. Backwater flooding at one such sink in Kiltartan in 2009 incurred an estimated cost of €540 000 to the local communities (Jennings O’Donovan & Partners 2011) and comparable damage was caused again during the winter of 2015–16.

**Overtopping of basins and sinks**

This flood mechanism is intrinsically linked to flooding within turlough and sink depressions because it occurs when floodwaters build up in surface depressions to such an extent that the level exceeds and overtops the surrounding topographic divide (Fig. 5b). When overtopping occurs, ephemeral overland flow routes develop, bypassing the groundwater flow systems normally governing water movement through the catchment. It thus differs from turlough and sink flooding in that the damage mechanism is hydrodynamic and relates to floodwaters moving across the landscape. This flood mechanism bears some similarity to the karst flash floods described by Bonacci et al. (2006), whereby overland flow plays the dominant part in flood formation and inter-basin overflow and/or redistribution of the catchment areas occurs due to rising groundwater. However, where flash flooding is typically in response to short (minutes to hours), high-intensity storms, the crucial recharge duration for the equivalent in lowland karst can be measured in weeks to months. This is due to the significant surface storage present within the gently undulating topography and low relief characteristic of the lowland landscape.

The delayed build-up of waters makes this mechanism easier to foresee than flash flooding, but that is not to say that it is easily preventable or managed. For example, a build-up of floodwaters around Kiltartan, south Co. Galway in 2009 caused overtopping of the N18 National Road with transient flow rates of $>30$ m$^3$ s$^{-1}$ (Fig. 7), forcing the closure of the highway and a nearby railway line for more than two weeks. Another example of overtopping occurred during the floods of 2015–16 further west in the Gort catchment at Caherglassaun turlough. Flooding within the turlough reached record depths of 14.6 m, causing overland discharge of $>5$ m$^3$ s$^{-1}$ northwards towards Cahermore, damaging properties along the flow route and around Cahermore turlough.

**Discharge from springs and resurgences**

Flooding in lowland karst aquifers can also be caused by high discharges of groundwater, via springs and resurgences, during which time the hydrodynamic force of the floodwater is the main cause of damage. This flood mechanism can be considered as groundwater-induced, in that flooding occurs due to intense groundwater discharge via springs or shallow, highly permeable horizons within the epikarst (Robins & Finch 2012). In lowland karstic systems, a distinction can be made between two discharge scenarios: (1) groundwater springs and risings on the periphery of upland areas exceeding normal discharge levels and causing flooding around and downstream of the resurgence (Fig. 5c); and (2) shallow flow paths within the epikarst zone are activated by high groundwater levels, triggering ephemeral springs and flooding of adjacent depressions (Fig. 5d).

The first scenario occurs where the lowland karst landscape is characterized by flat and undulating plains separated by isolated areas of higher ground,
such as can be found in Co. Roscommon and north Co. Galway. Here the recharge zones are located on topographic plateaus, which typically have thin or absent subsoil, have a high density of recharge landforms and a well-developed epikarst zone (Hickey 2010). Infiltration is transmitted through a well-developed epikarst system to springs located at the periphery of the upland areas, where groundwater is discharged via a combination of perennial and/or overflow springs. During periods of intense recharge, discharge from these peripheral springs can pose a significant flood risk. Excess spring discharge was the primary cause of groundwater flooding in Four Roads, Co. Galway, during November 2009. Springs discharging from the base of an adjacent karst plateau caused localized flooding around and downstream of the resurgence, inundating six houses and a community centre, as well as causing the prolonged closure of roads and limiting access to the local school.

The second scenario arises when elevated groundwater levels cause significant lateral flow through the uppermost weathered zone of the bedrock, the epikarst. Karst aquifers can have substantially enhanced and homogeneously distributed porosity and permeability in the epikarst (Klimchouk 2004). Under normal hydrological conditions this enhanced permeability plays an important part in regulating recharge to the phreatic zone by concentrating diffuse recharge towards areas of high vertical permeability. However, when phreatic groundwater levels rise sufficiently high, these pathways can transfer substantial lateral flows, giving rise to ephemeral springs and seeps in adjacent topographic depressions previously unaffected by flooding. This mechanism contributed to the flooding in Carnmone, Co. Galway in November 2009, when a series of temporary springs activated in response to high water levels in an adjacent turlough. Discharge from epikarst springs caused the flooding of four houses, with a further seven houses and two business premises at high risk. There was also a significant hydrostatic element due to the ponding of spring discharge, further highlighting that flooding in lowland karst groundwater systems is often the result of multiple mechanisms acting in combination.

Conclusions

Lowland karst groundwater systems represent a challenging environment from a flood risk
management perspective. The diversity of flood mechanisms identified in lowland karst terrains reinforces the need to develop a greater understanding of the complex hydrological and hydrogeological processes in operation during flood conditions. Although an important evidence base has been collated on groundwater flooding from recent extreme events, significant gaps remain in our knowledge. The first and most pressing is the lack of hydrological data, which could be addressed through the establishment of a permanent monitoring network to provide long-term quantitative data at flood-prone locations. Methodologies for improving groundwater flood hazard maps and real-time flood monitoring are also required. A prerequisite to effective flood risk management and mapping is the ability to monitor spatial and temporal changes in flood conditions and extent at a catchment scale. Traditional field-based methods are heavily reliant on labour-intensive, site-specific visits and instrumentation. The increasing ability and availability of remote sensing data, such as synthetic aperture radar, offers the potential to describe flood conditions quickly, accurately and at a large spatial scale, even over remote and rugged terrain.

The floods of 2009–10 and 2015–16 have brought into focus society’s close, and often turbulent, relationship with the water cycle in karst areas. Internationally, there has been increasing recognition of the flood mitigation benefits provided by functioning wetlands, nowhere more so than in the lowland karst landscapes of Ireland and the turloughs therein. However, the often-competing priorities of flood management and ecological conservation mean that inevitable conflicts lie ahead. An interdisciplinary approach is thus crucial to enable communities in lowland karst regions to develop the adaptation and mitigation strategies needed in the face of future climate uncertainty.

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