

Preliminary Flood Risk Assessments

June 2010 Office of Public Works



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MERTIT: for satellite imagery of flooding in the west and north-west.



Executive Summary

Background

The hazard of groundwater flooding in the Republic of Ireland has been assessed and a preliminary nationwide groundwater flood hazard map has been produced. The map shows the outlines of floods defined by applying a methodology developed specifically for the project to take account of the unique nature of the hydrogeological environment in the Republic.

Receptors have not been identified nor have risks and consequences been defined. These aspects of groundwater flooding form part of the next phase of work leading up to completion of preliminary flood risk assessments by December 2011.

Methodology

The methodology is based on a consideration of physical variables and hydrogeological environments nationwide as these control the amount, location and extent of groundwater floods. The evidence-based approach incorporates the experience of groundwater experts at the Geological Survey of Ireland, Trinity College Dublin, and the Environmental Protection Agency. It includes all other available sources of information and the findings of a search of literature published in Europe.

The evidence from the Republic of Ireland indicates that extensive, recurring groundwater floods originate at turloughs. These groundwater-fed, seasonal lakes are not found elsewhere in Europe. Their presence reflects a unique hydrogeological environment that has developed in certain limestone formations. Most of the 482 turloughs recorded by the Geological Survey of Ireland occur on the Pure Bedded Limestones Rock Unit Group which belongs, almost exclusively, to the regionally important aquifer dominated by conduit flow.

Turloughs are associated with two main regions: the lowland karst of the western lowlands in and around Counties Clare, Galway and southern Mayo; and the upland karst in the west, north-west and locally in the midlands. Turloughs also occur elsewhere at a few scattered locations across the country.

Groundwater flooding is particularly prevalent in the western lowlands near the town of Gort and between the River Fergus and Lough Bunny south-west of Gort. The floods near Gort are associated with a very well developed, complex, interconnected karstic drainage system. The turloughs in this area have been investigated by the Geological Survey of Ireland and by the Office of Public Works and are the subject of previous and on-going studies by Trinity College Dublin. The hydrogeological environment between the River Fergus and Lough Bunny is different from that near Gort and has not been studied in such detail. Karstification is less evident and there are fewer turloughs. Nonetheless, groundwater floods can be extensive and historic floods have occurred at similar times to those near Gort.



The methodology comprises a sequence of three stages based on different amounts of available information and, therefore, different accuracies of the mapped flood levels. The stages also take some account of regional variations in hydrogeology and potential recharge.

Stage 1: Use of Digital Images

Three digital images derived from aerial photography and three digital satellite images of historic floods in the west and north-west were made available. These cover relatively small areas of the country and the dates of the images do not necessarily coincide with the dates when groundwater floods were at their greatest extents.

Three of the images are for parts of the areas near Gort and between the River Fergus and Lough Bunny. The preliminary flood map in these areas has been drawn to coincide with the outlines of the most extensive floods shown on the images except in the area of Gort where the map has been adjusted at individual turloughs using data gathered during the severe flood in late 2009. There are a number of images of floods that are not associated with turloughs between the River Fergus and Lough Bunny. These floods have been included on the map because it is assumed that they have a groundwater origin, the exception being if they are located entirely on peat. Permanent water bodies have been excluded from the map.

A similar procedure based on a recent satellite image was used to map groundwater floods in the upland karst region.

Stage 2: Use of Statistical Approach

Approximate flood outlines were required for turloughs located outside the coverage of the images. The outlines were defined by assuming that flood levels are 4.0 m above the base elevations of the turloughs. This is the median difference between the base elevations of 85 turloughs on the database of the Geological Survey of Ireland that lie within the coverage of the images and corresponding flood levels. Contours on a Digital Terrain Model provided by the Office of Public Works were used to define the flood outlines. The few outlines that were obviously unrealistic were adjusted pragmatically. Sensitivity analysis based on the 90 percentile difference of 9.3 m was also carried out. This indicated that use of the median value gives realistic representations of likely flood outlines.

Stage 3: Use of Other Information

Some validation of the approach adopted for Stage 2 was obtained from an examination of flood reports that are kept on the Office of Public Works' database of flood events. There are 37 reports of turloughs with sufficient information to validate the approach. All the turloughs happen to be located in the western half of the country. The examination confirmed that most of the flood outlines are reasonable.



The methodology has taken regional variations in recharge into account by examining aerial photographs and historic maps of the 24 turloughs on GSI's database that are located in the eastern half of the country where recharge is relatively low compared with the west and northwest. Features attributable to groundwater flooding were identified and used to check flood outlines based on the +4.0 m contour derived from data in the west and north-west. Most flood levels associated with the 24 turloughs were significantly reduced as a result of the examination.

Other Approaches

Two other approaches to the mapping of groundwater flooding were considered but rejected. The use of areas of extreme and high vulnerability as surrogates for groundwater floods was rejected after it became apparent that the vast majority of floods are associated with turloughs. The mapping of areas encompassing springs and likely areas of shallow groundwater was rejected because there is no evidence that springs are a significant flooding hazard and the majority of their flow paths are short or very short. Also, there is virtually no data with which to accurately delineate areas of shallow groundwater.

Conclusions

The methodology to map groundwater flooding in the Republic of Ireland has been sufficiently flexible that issues of concern that were initially identified have been addressed and satisfactorily resolved. The nationwide groundwater flood hazard map can now be used in the next phase of work without further amendments.



1. Introduction

1.1 Project Background

The Floods Directive (2007/60/EC) came into force in November 2007. The Directive aims to assess and manage the consequence of flooding from all sources on human health, the environment, cultural heritage, economic activity and infrastructure. Groundwater flooding is covered by the general definition of a `flood' under Article 2(1) as `the temporary covering by water of land not normally covered by water'. The three main requirements of the Directive are for the competent authority of each member state to:

- undertake Preliminary Flood Risk Assessments (PFRAs) by December 2011
- develop flood hazard and risk maps by December 2013
- produce flood risk management plans (FRMPs) by December 2015.

The Office of Public Works (OPW), as the competent authority in the Republic of Ireland with respect to the Floods Directive, has completed pilot catchment based flood risk assessment and management (CFRAM) studies and PFRAs in areas where the risk of flooding is considered to be the greatest. The results of these studies have informed OPW's strategy for producing PFRAs and FRMPs on the national scale. The general strategy for PFRAs is as follows:

- use historic data and information to define areas most at risk of flooding
- consult with reputable sources of local knowledge on flooding, and with stakeholders with specific interest in particular receptors (e.g. cultural or environmental assets)
- use predictive data to define areas that might be prone to flooding based on modelling, analysis of topography, soil types, etc.

To date, the assessment of flood risk for the PFRAs has largely been with respect to fluvial, pluvial and coastal flooding. The risk of groundwater flooding on a national scale has not been considered in any detail. However, although groundwater flooding is relatively insignificant compared with other forms of flooding in the east and south, it is not uncommon in the west and north-west. Therefore, it is important that groundwater flooding is included in FRMPs and considered in the context of the general strategy for PFRAs summarised above.

This report sets out the approach used to assess groundwater flooding in the Republic of Ireland, describes the assessment, the methodology that was developed in order to create a preliminary GIS based map, and the map itself.

The approach is based on a source – pathway – receptor – consequence conceptual model of groundwater flooding. A combination of the source and pathway is the hazard (`a situation that in particular circumstances could lead to harm') and risk is `a combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of the occurrence'.

The report summarises the first phase of work carried out between January and March 2010. This initial phase has concentrated on defining the groundwater flooding hazard, rather than the risk of groundwater flooding. The next phase, which is due for completion in December 2011, will comprise the identification of receptors and the definition of risk and consequence with respect to groundwater flooding so that this type of flooding can be incorporated into PFRAs and FRMPs at the appropriate scale.



1.2 Project Objectives and Scope of Work

The principal project objective is to incorporate groundwater flooding into PFRAs. The objectives of the first phase of the project, as described in this report, are to assess the extent and scale of the groundwater flooding hazard across the Republic of Ireland and to produce a preliminary GIS based map of this hazard.

The scope of work for the first phase of the project encompasses the following:

- A comprehensive literature review of groundwater flooding and approaches to it adopted in other countries of the European Union (EU) in order to fulfil the requirements of the Directive.
- Development of a methodology for assessing the groundwater flooding hazard appropriate to the groundwater conditions in the Republic of Ireland based on:
 - A detailed understanding of the hydrogeology,
 - A positive and negative evidence based approach founded on:
 - the experience of groundwater experts at the Geological Survey of Ireland (GSI),
 Trinity College Dublin (TCD) and the Environmental Protection Agency (EPA),
 - interrogation of the database <u>www.floodmaps.ie</u> and the experience of OPW staff both nationally and regionally,
 - the contents of both published and unpublished sources of information.
- Use of the methodology to produce a preliminary GIS based map of groundwater flooding.
- A report describing the first phase of the project and including detailed recommendations for further work.

1.3 Outline of Report

Following this introduction, Chapter 2 reviews the climate and physical setting of the Republic of Ireland since both are of relevance to groundwater flooding. They are the source term, and can influence the pathway term, in the source – pathway – receptor – consequence model.

Chapter 3 presents a general review of the geology and hydrogeology of the Republic of Ireland. The latter is particularly important because it is the pathway term in the source – pathway – receptor – consequence model.

Chapter 4 comprises a review of groundwater flooding in Europe and describes the approaches to mapping that have been adopted in the UK.

Chapter 5 discusses the occurrence of groundwater floods in the Republic. Chapter 6 explains the methodology used to produce the groundwater flood map and describes the map.

Chapter 7 sets out the principal conclusions of the initial phase of the project and makes detailed recommendations for work to be carried out during the next phase. References are listed after Chapter 7, followed by appendices.



2. Physical Geography

2.1 Climate

The climate of the Republic of Ireland is mild, moist and changeable with abundant rainfall and comparatively rare temperature extremes. Summers are generally warm and the winters are mild due to the warming influence of the Gulf Stream. There is regional variation, with inland areas being warmer in summer and cooler in winter than their coastal counterparts. The prevailing winds blow from the south-west and break on the mountains of the west coast where some parts receive over four times as much rain as the east coast.

The principal climate variables of relevance to groundwater flooding are those that control the amount of recharge, this being the portion of precipitation that is not lost to evapotranspiration, soil moisture deficits or runoff, but passes through the soil zone into the subsurface where it eventually becomes groundwater.

Rainfall is the most common form of precipitation. Most of the eastern half of the country receives between 750 and 1000 mm/yr compared with 1000 to 1250 mm/yr in the west. In many mountainous districts totals exceed 2000 mm/year. Of the 13 synoptic weather stations in the Republic, it is Valentia Island in County Kerry which is the wettest, with a long term average is 1430 mm/year. The driest station is at Dublin Airport with an average of 711.4 mm/year. 2009 was the wettest of the last five years at Valentia Island, the annual total being 2175 mm. The wettest months almost everywhere are December and January.

Actual evapotranspiration ranges between about 400 to 500 mm/year across the country. Therefore, there is an excess of precipitation over evapotranspiration in the order of 350 mm/year (in the east) to 850 mm/year (in the west). This is clearly a large amount of potential recharge, notwithstanding some losses to soil moisture deficits and runoff. There is also a significant difference in the amount of potential recharge across the country.

Thus, from the perspective of potential recharge amounts, groundwater flooding is a possibility across the Republic. However, flooding in the west is likely to be more extensive and occur more frequently than in the east.

A further consideration is that precipitation is often rapidly transferred to the subsurface as bypass flow with little losses to actual evapotranspiration in those parts of the country underlain by karstic limestone. The effects of karstic environments on the movement of water through the subsurface are fundamental to groundwater flooding and are given due consideration in later chapters of this report.

2.2 Physical Setting

The physical setting of the Republic of Ireland reflects the tectonic history, structure and composition of the underlying bedrock and the history of glacial and post-glacial erosion and deposition that has occurred from the Quaternary Period until the present.

The main topographic features comprise low lying central plains and surrounding coastal mountains, the highest peak being Carrantuohill in County Kerry. The western coastline is rugged, with many islands, peninsulas, headlands and bays.

The large central lowland area is principally underlain by limestone which is covered by glacial deposits that vary both in thickness and composition depending on their provenance and history. Bogs and lakes are



common, the Bog of Allen being one of the largest bogs in the country. Ground elevations in the central lowland area lie below about 120 mAOD.

In the south, the coastal mountains are composed of Old Red Sandstones. Further inland, mountains such as the Galtee, Silvermines and Slieve Bloom Mountains are composed of folded sedimentary rocks of Carboniferous age. In Counties Galway, Mayo, Donegal and Wicklow the mountains are mainly of granite. The mountains are not high; although ground elevations are above 600 mAOD only three peaks are above 1000 mAOD. Karstic limestones are a distinctive feature of the Irish landscape, particularly in the west and north-west in Counties Sligo, Mayo, Roscommon, Galway and Clare. The north-west plateau karsts in County Sligo, and the Burren in northern County Clare, form relatively high ground above 300 mAOD.

The soils in the north and west tend to be poorly drained peats, gleys and some peaty podzols. In contrast, the soils in the south and east are free-draining brown earths and podzols.

The River Shannon is the longest river in the Republic of Ireland, being 386 km in length and flowing south from above Lough Allen to join the Atlantic Ocean beyond Limerick. The four largest lakes along its course are Loughs Allen, Bofin, Ree and Derg. Other major rivers include the Boyne, Liffey, Slaney, Barrow, Nore, Suir, Blackwater and Lee. Other large lakes include Loughs Conn, Mask and Corrib in Counties Galway and Mayo.

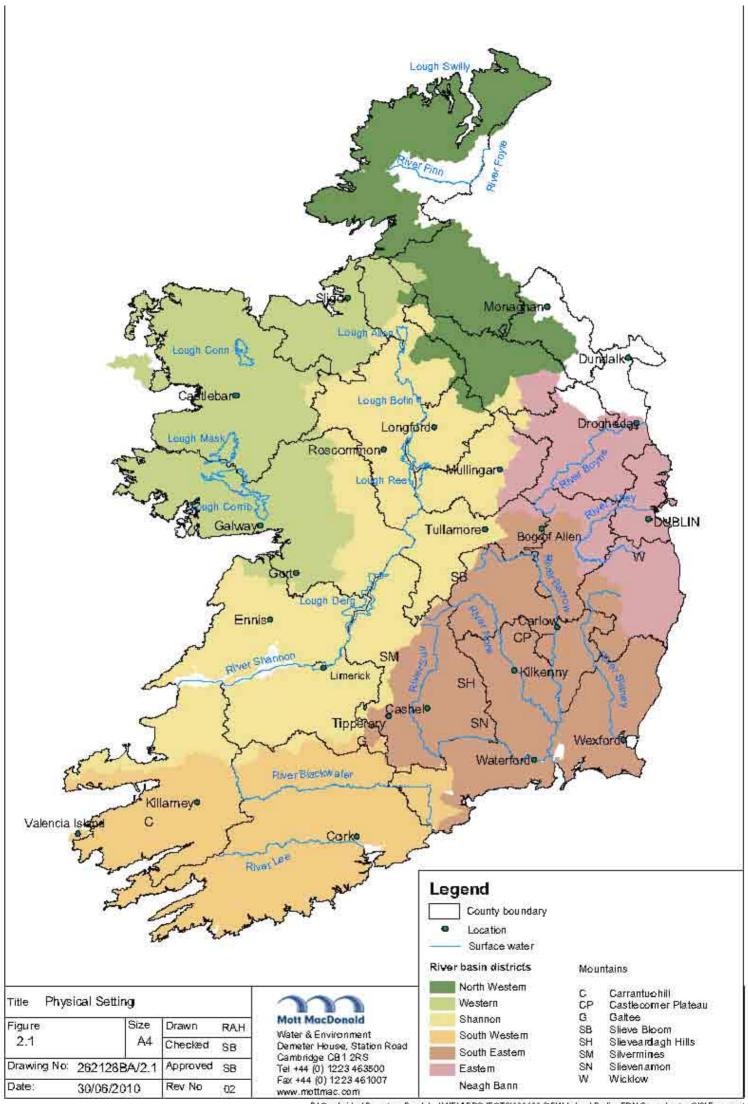
2.3 Administration and Data Collection

Met Éireann is the Irish national meteorological service. Standard meteorological variables are recorded on an hourly basis at 13 synoptic stations across the Republic of Ireland and potential evapotranspiration, evaporation and soil moisture deficits are calculated on a daily basis at these stations. There are also about 750 rainfall stations where daily records are taken.

The Water Framework Directive (WFD), which established a new framework for the EU community in the field of water policy, came into force in December 2000. The EPA is the competent authority for coordination and reporting nationally with local authorities acting jointly to develop management plans and programmes of measures. The Directive provides for effective water management on the basis of River Basin Districts (RBDs). Eight RBDs were established on the island of Ireland [EPA and RBD coordinating authorities, 2005] in June 2004. Of these, three are international RBDs (Shannon, North Western and Neagh Bann), one lies solely in Northern Ireland, and the remaining four are solely in the Republic.

As part of its responsibilities with respect to the WFD, EPA collects and processes various data sets, including stage and flow at numerous surface water gauging stations across the Republic of Ireland. The data for 200 gauged sites are `live' on the EPA's webpage hydronet.epa.ie. This is a useful resource for defining regional variations, seasonal variations and the timing and size of extreme events.

The information given in this chapter is summarised in Figure 2.1.





Hydrogeology

3.1 Introduction

This chapter outlines the geological and hydrogeological environment within the Republic of Ireland. This environment is the pathway component in the source-pathway-receptor model of groundwater flooding and is therefore central to the evaluation of such flooding.

The complex geology of the Republic of Ireland reflects its very long history of deposition, alteration, structural deformation and erosion with two thirds of the geological periods from the Precambrian to the Quaternary represented in the geological record.

The standard method of geological classification considers rocks (termed "bedrock") deposited prior to the Quaternary period separately from sedimentary strata (termed "drift", "superficial deposits" or "subsoils") deposited in the following 2.6 million years to the present. These two types of deposits, their occurrences and their structural histories are summarised in Sections 3.2 and 3.3. Their hydrogeological characteristics are described in Section 3.4.

3.2 Bedrock Geology

More than 1200 geological Formations and Members have been defined in the Republic of Ireland. This unwieldy number has been reduced to 27 "Rock Unit Groups" (RUGs) by GSI's Groundwater Section on the basis of geological characteristics that have hydrogeological relevance. These groups are shown on the generalised bedrock map produced by the groundwater section of the GSI, reproduced here as Figure 3.1. GSI [2009 (draft)] has documented the characteristics of the groups and this substantial body of work has informed the general geological description given below. Details of each group are provided in Appendix A.

The bedrock geology of the Republic of Ireland comprises a variety of distinctive sedimentary rock types that are characteristic of particular depositional environments, igneous and volcanic rocks that have been emplaced within the sedimentary sequence, and rocks changed from their original state by deformation and heat – the metamorphic rocks.

The two oldest Precambrian groups comprise metamorphic marbles, quartzites, gneisses and schists which have undergone at least eight phases of major faulting and folding. They are present in County Donegal, and parts of Galway, Mayo and Wexford.

The sedimentary history of the Lower Palaeozoic era relates to marine sedimentation on either side of a slowly closing ancient sea. There are four RUGs of Lower Palaeozoic age. Ordovician slatey mudstones and Silurian muddy sandstones, siltstones, mudstones and shales were deposited in the north-west and now occupy the Longford-Down Inlier. Cambrian, Ordovician and Silurian metasediments and Ordovician volcanic ashes were deposited in the south-east and now occupy the Campile Syncline. Both the Longford-Down Inlier and Campile Syncline are complexly folded and faulted structures with south-westerly to north-easterly trending fold axes and faults that formed during the Caledonian orogeny at the end of the Silurian period and were subsequently modified during the Varsican orogeny at the end of the Carboniferous period.

The Upper Palaeozoic era commenced with the accumulation of a thick sequence of Devonian sandstones, siltstones, shales and conglomerates (the Old Red Sandstone, ORS) that was deposited by river systems in a sub-equatorial arid environment. The deposits infilled the Munster Basin in the south and other smaller



basins in the midlands and north. There are two RUGs of Devonian age: the Kiltorcan-type Sandstones which is a subset of the ORS, and the ORS itself.

The sedimentary environment changed at the beginning of the Carboniferous period when the Devonian landmass became covered by a shallow sea. A variety of rock types were laid down in different parts of the sea during the Dinantian stage. More than half of the country is underlain by these rocks. There are ten RUGs which include limestones, sandstones, siltstones, mudstones, shales and evaporites. The limestones have the greatest areal extent. Their lithologies and sedimentary structures are very variable. For example, some are pure while others contain silts, and some are bedded while others are massive. These differences have influenced the subsequent permeability development within the rocks. In particular, karstic features are well developed in some limestones but poorly developed or absent in others. Limestone deposition ceased at the end of the Lower Carboniferous, probably because of climate change. Deposition of fossiliferous shales, siltstones and sandstones continued in deep offshore basins that gradually filled during Namurian times. This was followed by the deposition of terrestrial sandstones and shales in a deltaic and swampy environment during Westphalian times. Coal seams formed subsequently from vegetation that accumulated in this environment.

The Variscan orogeny at the end of the Carboniferous period imposed a complex structure of folds and faults on the Palaeozoic sequence, the older rocks of which were already folded and faulted as a result of the Caledonian orogeny. Variscan fold axes trend in a westerly to easterly direction in the south, for example in the area of Cork and beneath the Galtee Mountains, and veer to a more south-westerly to north-easterly direction further north beneath the Slieveardagh Hills and the Castlecomer Plateau. Folds are tight in the south, because the compressional stress originated in the south, and fade northwards. The extensive subcrop of Pure Bedded Limestones in the west and north-west is relatively horizontal. Variscan faults are common throughout the Palaeozoic sequence, although the more brittle rock types have fractured more than the less brittle types. Faults have a dominantly north to south orientation in the south, veering to a more north-westerly to south-easterly orientation further north.

The youngest sedimentary RUGs in the Republic of Ireland comprise several Permo-Triassic groups of sandstones and mudstones and gypsum. The rocks are relatively scarce, occupying only about 0.05% of the country. There are no Jurassic, Cretaceous, Palaeogene or Neogene aged rocks in the Republic, although some are present in Northern Ireland.

Granites and other intrusive rocks, and basalts and some other volcanic rocks belong to two separate RUGs. Four areas of the Republic of Ireland have major granite intrusions: the Leinster Granite, the Donegal Granite, the Galway or Connemara Granite, and the Newry and Carlingford Granites. All the granites except for the Carlingford Granite were emplaced during the Caledonian orogeny. The Carlingford Granite was emplaced during the Tertiary era about 60 million years ago. The group of basalts and some other volcanic rocks are of Carboniferous age and formed as lava flows and layers of silica rich, vesicular tuff. The rocks occur in widely scattered small areas that in total form only a small part of the country.

3.3 Subsoils

Approximately 90% of the bedrock in the Republic of Ireland is overlain by unconsolidated deposits dating from the Quaternary period to the present, referred to as subsoils [EPA and RBD Coordinating Authorities, 2005]. These are highly variable in distribution, composition, thickness, permeability, provenance and the depositional processes that formed them. Subsoils are shown on a recent Teagasc map provided by EPA and reproduced here as Figure 3.2. The main subsoil types, the proportion of the country covered by each type, and general geological descriptions of each type are summarised below.



Glacial tills (62.5% of the country) are comprised of ground-down debris deposited by or from glacier ice and are usually derived from the underlying bedrock material at any location. Thus, their properties are usually related to those of the underlying bedrock. For example, clay rich till occurs above shales and mudstones, and sandy till occurs above sandstones. Tills are generally unsorted with a wide range of grain sizes and significant primary porosity. Till sequences can be quite complex, for example a lithological log for the Rathduff borehole in the South Eastern River Basin District (SERBD, see Tedd et al, 2010) has 18 m of clay, sand, limestone till and gravel overlying the Dolomitised Limestone bedrock. Till thicknesses are very variable across the country, ranging from less than 10 m to more than 40 m. Depths to bedrock tend to decrease with increasing elevations and bedrock is often exposed in upland areas.

Sand and gravel deposits (4.3% of the country) are widely scattered across the Republic of Ireland and are described in detail in Chapter 26 of GSI [2009 (draft)]. The five areas where the deposits are more extensive than elsewhere are described in Appendix B. These areas are all located in the SERBD and are described by Tedd et al [2010]. The deposits have either a glacial origin, and are relatively unsorted and less permeable, or a glacio-fluvial or entirely fluvial origin and are better sorted and more permeable. The deposits generally comprise poorly sorted, coarse grained sand and gravel with varying amounts of interbedded clay and silt. Thicknesses vary between less than about 10 m to 40 m with extreme thicknesses of more than 100 m proved at a few locations.

Alluvium (0.6% of the country) is entirely fluvial in origin. It is generally younger than glacial subsoil but is often found alongside or overlying it, forming long, narrow deposits between about 20 m and 200 m wide on both sides of major river channels. Alluvium has a very variable composition, from silts to coarse gravels, and is generally up to 2 m thick, although thicknesses of up to 15 m do occur. There are exceptions to this. For example, the extensive deposit of sands and gravels along the River Barrow valley (see Appendix B) is believed to be fluvial in origin but is several kilometres wide and up to 25 m thick.

Extensive postglacial deposits of peat (18.9% of the country) are widespread but more common in the midlands and north. The peat varies in composition and form, depending on the local climate, topography and underlying subsoil. However, by their nature, all peats are organic rich and relatively impermeable. Thicknesses are generally less than 10 m.

Other subsoil types are of minor areal extents and include lacustrine silts and clays (0.4%), beach / wind blown sediments (0.2%) and made ground (1.2%).

3.4 Classification of Aquifers

The system of bedrock aquifer classification in Ireland was developed by the GSI more than ten years ago, see for example DEHLG/EPA/GSI [1999], Wright [2000] and Fitzsimons et al [2005]. Aquifer classification was initially undertaken on a county by county basis. A National Aquifer Classification Programme (NACP) was then undertaken for the WFD which was completed in 2004. A draft national bedrock aquifer map was published in early 2005 and updated draft versions were issued in 2009 and early 2010. The latest aquifer map, which includes the sand and gravel subsoil aquifers, is reproduced here as Figure 3.3.

The classification system is based on the flow type and resource potential of the bedrock and was developed primarily using tested geological and hydrogeological assumptions. There are three main groups (describing resource value), encompassing seven bedrock aquifer categories and two sub-types that characterise the groundwater flow regime and resource potential of the 27 RUGs described in Section 3.2 above. Two additional categories are included to take account of sand and gravel deposits since this subsoil is a significant aquifer at both the regional and local scales.



The groups, categories and sub-types are as follows:

Regionally Important (R) Aquifers

- Karstified bedrock (Rk)
 - Karstified bedrock dominated by diffuse flow (Rk^d)
 - Karstified bedrock dominated by conduit flow (Rk^c)
- > Fissured bedrock (Rf)
- > Extensive sand and gravel (Rg)

Locally Important (L) Aguifers

- Karstified bedrock (Lk)
- Bedrock which is Generally Moderately Productive (Lm)
- Bedrock which is Moderately Productive only in Local Zones (LI)
- Sand and gravel (Lg)

Poor (P) Aquifers

- Bedrock which is Generally Unproductive except for Local Zones (PI)
- Bedrock which is Generally Unproductive (Pu)

General aquifer properties of the 27 RUGs and the sand and gravel deposits are included with the geological descriptions given in Appendices A and B. The descriptions are condensed from GSI [2009 (draft)]. Generalised descriptions of the aquifer groups, provided by GSI in early 2010 and based on Hunter Williams and Lee [2008], are given in Appendix C.

The terms are all self-explanatory, except, perhaps, for `karst'. GSI defines karstification as the process whereby limestone is slowly dissolved away by percolating waters along certain fractures, fissures and joints at the expense of others. Karstification frequently results in the uneven distribution of permeability and drainage that is largely underground with most flow occurring through solution-enlarged, interconnected zones of fissures and, in some limestones, of conduits. The degree of karstification ranges from slight to intense and GSI recognises two types of karstic aquifer: that dominated by diffuse flow (Rkd) and that dominated by conduit flow (Rkc).

The sand and gravel deposits are, because of their young age and composition, classified as subsoil, although the deposits may be classified as aquifers if they meet certain area and thickness criteria. All other subsoils in the Republic of Ireland are treated differently by GSI and EPA despite the fact that some are moderately permeable and, where sufficiently thick, have potential as a resource. The approach adopted by GSI and EPA has been to consider all the other subsoils in terms of their potential to protect underlying groundwater from surface contamination.

Typical aquifer categories for each of the bedrock RUGs have been provided by GSI and are given in Table 3.1. Summary statistics for the aquifer groups are given in the National Summary Report [EPA and RBD Coordinating Authorities, 2005]. This report summarised the large body of work carried out during implementation of the WFD and included the characterisation of RBDs and 757 groundwater bodies. The summary statistics are as follows:

•	Percentage area where groundwater flow is in karstic aquifers	16.2%
•	Percentage area where groundwater flow is in productive fissured bedrock	7.4%
•	Percentage area where groundwater flow is in sand and gravel	2.0%



Percentage area where groundwater flow is in poorly productive bedrock

71.0%

Table 3.1: Rock Unit Groups and Typical Aquifer Categories

Rock Unit Group	Typical Aquifer Category
Permo-Triassic Sandstones	Lm
Permo-Triassic Mudstones and Gypsum	PI
Westphalian Sandstones	Lm
Westphalian Shales	Pu
Namurian Shales	PI, Pu, limited LI
Namurian Sandstones	LI, PI, limited Lm
Namurian Undifferentiated	LI, PI, limited Lm
Dinantian Shales and Limestones	LI, PI, some Lm (border area)
Dinantian Mixed Sandstones, Shales and Limestones	LI, limited Lm
Dinantian Sandstones	Mostly Lm, some Ll
Dinantian Pure Bedded Limestones	Rkd (south), Lk, Ll, Rkc (west)
Dinantian Upper Impure Limestones	LI, PI, Lm (north Dublin area)
Dinantian Dolomitised Limestones	Rkd, Lk
Dinantian Pure Unbedded Limestones	Rkd/Lk (south), Ll (midlands)
Dinantian Lower Impure Limestones	Mostly LI, some Lm (midlands) some Rf (border)
Dinantian (early) Sandstones, Shales and Limestones	LI, PI, Rf (Limerick area)
Dinantian Mudstones and Sandstones (Cork Group)	LI
Devonian Kiltorcan-type Sandstones	Rf (Lm)
Devonian Old Red Sandstones	PI (south), LI (midlands)
Silurian Metasediments and Volcanics	PI, LI, Pu
Ordovician Metasediments	Pl, Ll, Pu
Ordovician Volcanics	Rf (southeast), mostly PI elsewhere, also LI, Lm
Cambrian Metasediments	Pl
Precambrian Quartzites, Gneisses & Schists	PI, limited Pu
Precambrian Marbles	Mostly PI, some LI
Granites & other Igneous Intrusive rocks	PI, LI (parts of Carlow)
Basalts & other Volcanic rocks	Ll, Lm

3.5 Subsoils and Groundwater Vulnerability

An assessment of groundwater vulnerability is a measure of the ease with which groundwater may be contaminated by human activities (DEHLG/EPA/GSI [1999]; Fitzsimons et al, [2003]; Working Group on Groundwater [March 2005]). In bedrock aquifers, it is determined either by the thickness and permeability of the subsoils below the point of release of contaminants, or, if present, by the proximity of karst features. In unconfined sand and gravel aquifers it is determined by the thickness of the unsaturated zone below the point of release.



Groundwater vulnerability in the context of potential groundwater flooding is of interest because of the likely inverse relationship between the two with respect to recharge. In general, groundwater bodies with low vulnerability are not likely to flood because recharge to them is limited and slow [Fitzsimons and Misstear, 2005], and interaction between groundwater and surface water is limited by the presence of thick, low permeability subsoils.

More than 90% of Ireland is covered by subsoils [EPA and RBD Coordinating Authorities, 2005]. However, these subsoils are highly variable in distribution, composition, permeability and thickness as described in Section 3.3 above. This is demonstrated by the complexity shown on GSI's latest groundwater vulnerability map which is reproduced here as Figure 3.4. This map is continually evolving as new areas are mapped. Four vulnerability categories are defined in DEHLG/EPA/GSI [1999]. The extreme category, however, is further delineated on the maps into two categories ("rock close/karst" and "extreme"). Interim vulnerability maps have been introduced for counties where full groundwater vulnerability mapping does not exist, introducing the 'high to low' category.

The original categories of extreme and high vulnerability occupy about 6.5% of the country underlain by aquifers other than poorly productive ones [EPA and RBD Coordinating Authorities, 2005]. This percentage appears rather low compared with the extent of the extreme category shown on Figure 3.4. Nonetheless, if vulnerability were to be used as an indicator of potential groundwater flooding, this low percentage would suggest that such flooding would be on a relatively small scale and therefore not of particular concern. However, it is noted that bypassing of overlying protective subsoils may occur at karstic features.

3.6 Observed Groundwater Levels

The position of the water table relative to the ground surface is the principal indicator of whether or not groundwater flooding is likely for those aquifers whose characteristics are conducive to it. The position of the piezometric surface shows the level to which groundwater would rise in, for example, a well, were it not confined. Thus, for both confined and unconfined groundwater environments, the analysis of groundwater levels is a fundamental tool for the mapping of groundwater flooding.

An exception is the groundwater environment underlain by karstified aquifers dominated by conduit flow where conventional piezometric surfaces may be absent [Drew 2008, Southern Water Global 1997, Drew and Daly 1993]. In this environment, the measurement of water levels is only relevant if the measuring points are actually located in conduits. This is very rarely the case.

Monitoring of groundwater levels and the collation of data nationwide became the responsibility of the EPA in 2006 in accordance with Article 8 of the WFD. Information and water levels for about 120 sites are currently held on the EPA's WISKI database. Monitoring only started at the majority of these sites in 2007 and datum levels have not yet been surveyed to Ordnance Datum. Spreadsheets of raw data were provided by EPA. A summary of water levels at 24 sites of relevance to this project is given in Table 3.2.

There are four EPA sites where groundwater level minima are less than 2 m below the ground surface, namely BH 13_012, BH 08_006, BH 16_014 and BH 17_008. The sites are all in low lying areas close to surface water courses. Thus, analysis of the EPA data indicates that shallow groundwater levels do occur in various aquifers scattered across the Republic of Ireland. However, the sparsity of the monitoring points obviously means that the EPA data cannot be used as a tool for the mapping of groundwater flooding on a regional scale.



Table 3.2: Selected EPA Groundwater Monitoring Point Summary

EPA BH	Easting	Northing	Geology	Aquifer Type	Max WL (mBGL)	Min WL (mBGL)	Record Start	Record End
13_012	164407	156656	Dinantian Pure Unbedded Limestones	Rkd	1.95	0.45	15/04/08	22/01/10
08_006	100190	87948	Dinantian Pure Unbedded Limestones	Rkd	2.49	0.38	16/04/08	13/10/09
09_007	266589	238032	Dinantian Upper Impure Limestones	Lm	4.90	2.16	12/06/08	04/02/10
12_001	186903	356268	Dinantian Sandstones	Lm	11.83	9.27	25/09/08	01/02/10
15_007	321700	308100	Dinantian Mixed Sandstones, Shales and Limestones	Lm	4.92	3.56	19/03/08	14/01/10
16_003	112000	340500	Dinantian Sandstones	Lm	3.08	2.31	17/09/08	17/12/09
16_014	120200	329700	Dinantian Sandstones	Lm	1.91	0.67	26/06/09	17/12/09
17_003	295493	253169	Dinantian Upper Impure Limestones	Lm	20.17	3.31	10/04/08	22/01/10
17_008	311345	272750	Dinantian Upper Impure Limestones	Lm	2.40	0.41	08/04/08	29/01/10
18_003	258100	340100	Dinantian Pure Bedded Limestones	Lk	47.71	37.20	20/03/08	26/01/10
18_004	259100	340500	Dinantian Pure Bedded Limestones	Lk	35.31	31.12	09/09/08	26/01/10
18_005	257700	329600	Dinantian (early) Sandstones, Shales and Limestones	Rf	6.05	3.92	20/03/08	18/01/10
18_009	258100	341200	Dinantian Mixed Sandstones, Shales and Limestones	LI	69.77	63.63	20/03/08	26/01/10
18_011	257700	340700	Dinantian Mixed Sandstones, Shales and Limestones	LI	46.92	42.43	19/03/08	13/01/10
27_005	328743	206824	Cambrian Metasediments	PI	11.68	8.42	22/09/08	03/02/10
27_008	329292	207120	Cambrian Metasediments	PI	11.11	10.00	22/09/08	03/02/10

Other sources of groundwater level data include some of the descriptions of groundwater bodies available on www.gsi.ie, and a GSI database of water levels that includes a few records of more than 30 years duration. Tedd et al [2010] reviewed groundwater levels at 46 monitoring boreholes in SERBD. The review identified five boreholes where minimum levels are less than 2 m below the ground surface, as summarised in Table 3.3.

Table 3.3: Shallow Groundwater Levels in SERBD

ВН	Easting	Northing	Geological Name	Aquifer	Max WL (mBGL)	Min WL (mBGL)
Oldtown	238700	154400	Kilmanagh Sands and Gravels	Rg	3.43	0.81
Granston Manor	234100	178600	Crosspatrick Formation	LI	4.20	0.00
Tubbrid Lower	234230	161920	Ballyadams Formation	Rkd	4.91	0.62
Cullahill	237400	175700	Durrow Formation	LI	6.60	0.31
Land Commission 2	259300	193100	Ballyadams Formation	Rkd	42.06	1.05

Tedd et al [2010] included a detailed analysis of the data and an examination of the hydrogeological environment around all 46 boreholes. A re-examination of the hydrogeological environment around the five boreholes listed in Table 3.3 suggests that four of the five borehole sites may be susceptible to groundwater flooding. The four sites are all located close to surface water courses. However, although this information could be used to map flooding susceptibility at the local scale close to the sites, it cannot readily be extrapolated to the national scale because, apart from being close to surface waters, there are no obvious hydrogeological features common to the four sites.



3.7 Springs

Springs are very common across the country, although their locations and characteristics are very variable, reflecting the different hydrogeological environments where they are located. Springs occur where the water table surface intersects the ground surface. Therefore, springs are locations that may be susceptible to groundwater flooding. The Ordnance Survey of Ireland (OSI) holds the most comprehensive database of spring locations and these were made available to OPW for use in this project. There are about 50,000 springs on the database, and these are shown on Figure 3.5 (they are colour coded according to which aquifer categories they rise on).

The hydrogeological environments of springs are described in GSI [2009 (draft)] and springs are referred to in reports characterising groundwater bodies. This published information is very general in its nature and groundwater flooding is not mentioned anywhere.

Seven areas distinguished by their aquifer categories and relatively high spring densities have been studied in some detail in an attempt to understand the relationships between the springs, their hydrogeological environments, and their propensity to flood. The areas are shown on Figure 3.5.

Area 7 in County Cork is typical of the complexity of the situation. The springs feed surface watercourses (see Figure 3.6 a, although very small watercourses are not shown). Figure 3.6 b indicates that the springs are scattered across the subcrop of all the bedrock formations in the area, although the spring density is higher across much of the Ballytrasna Formation (a formation within the ORS) in the north. The whole area is covered by subsoils of sandy till (Figure 3.6 c) and therefore these subsoils may be a controlling factor in the locations of the springs. Faulting and fracturing may also have an influence.

The studies carried out in the seven areas have shown that relationships between springs and their hydrogeological environments are complex and that little information concerning the propensity of the springs to flood can be obtained from these types of studies. A more detailed field-based approach that examines the detailed hydrogeological environments of individual springs may prove worthwhile. This would be an ideal subject for an academic study.

The high density of springs suggests that most of the corresponding groundwater flow paths are short or very short. This means that spring flows are likely to be relatively small and unlikely to cause flooding. Exceptions to this are some springs that issue from karstic flow systems. However, there is no evidence that significant groundwater flooding is associated with springs anywhere in the Republic. Therefore, it is assumed that, although locations where springs rise may be susceptible to groundwater flooding, if this does occur it is at a very local scale that can be ignored in the first phase of groundwater flood mapping.

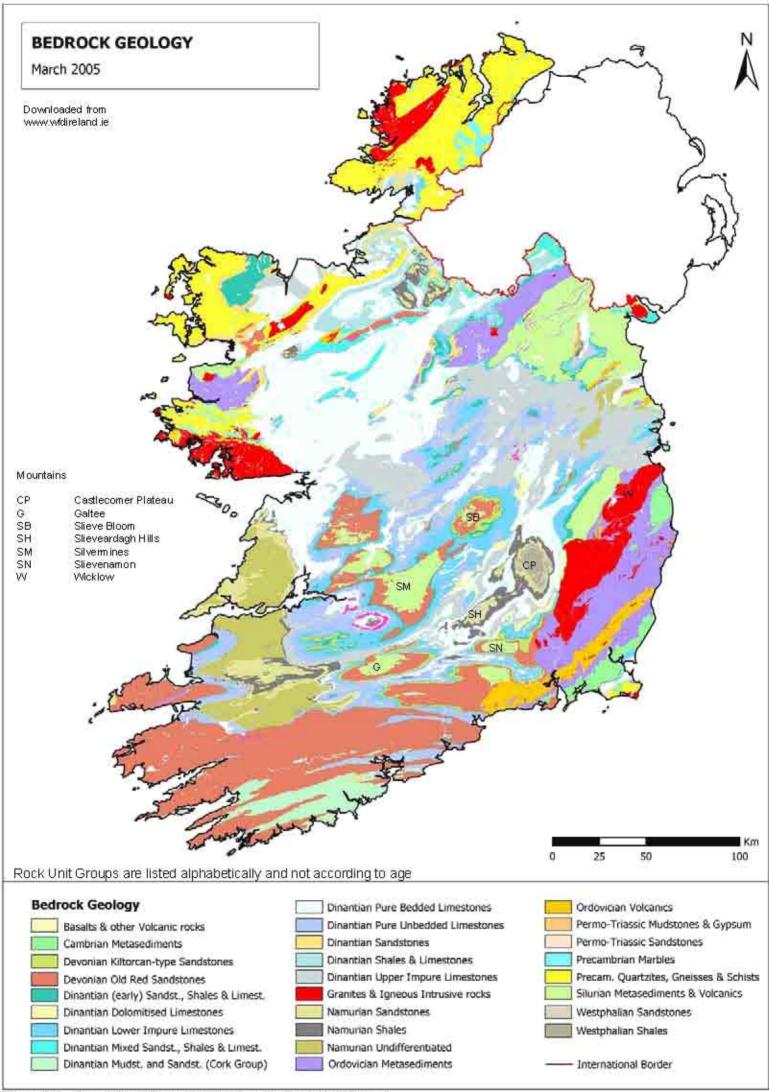
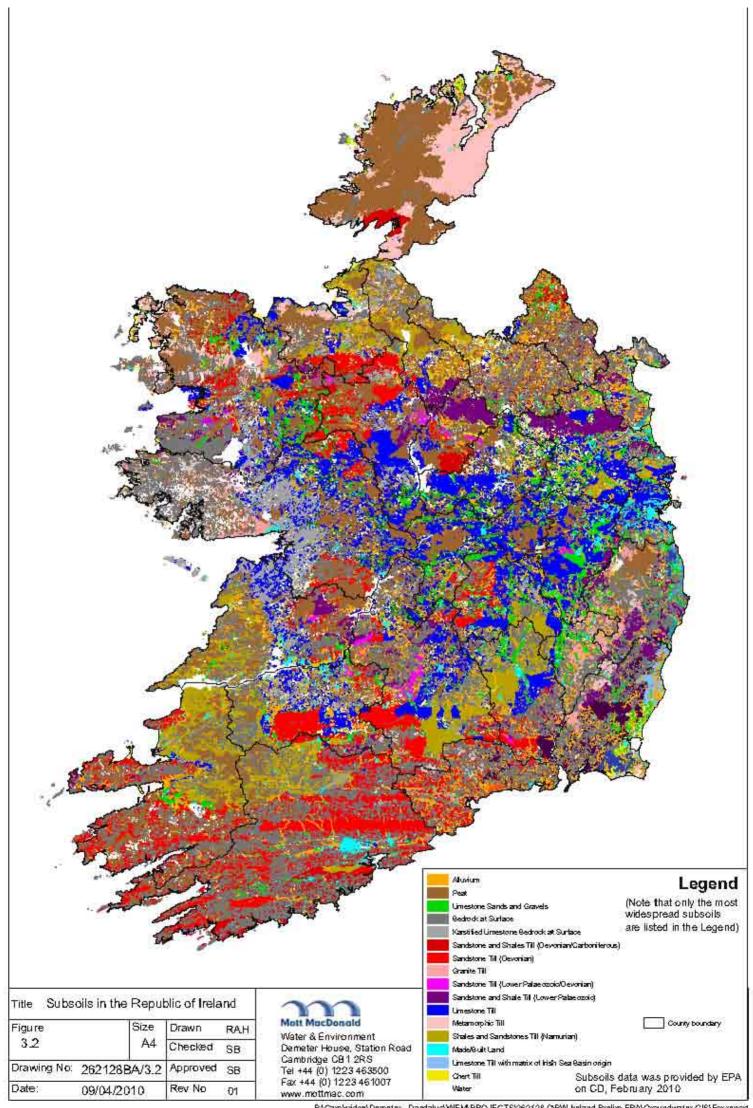
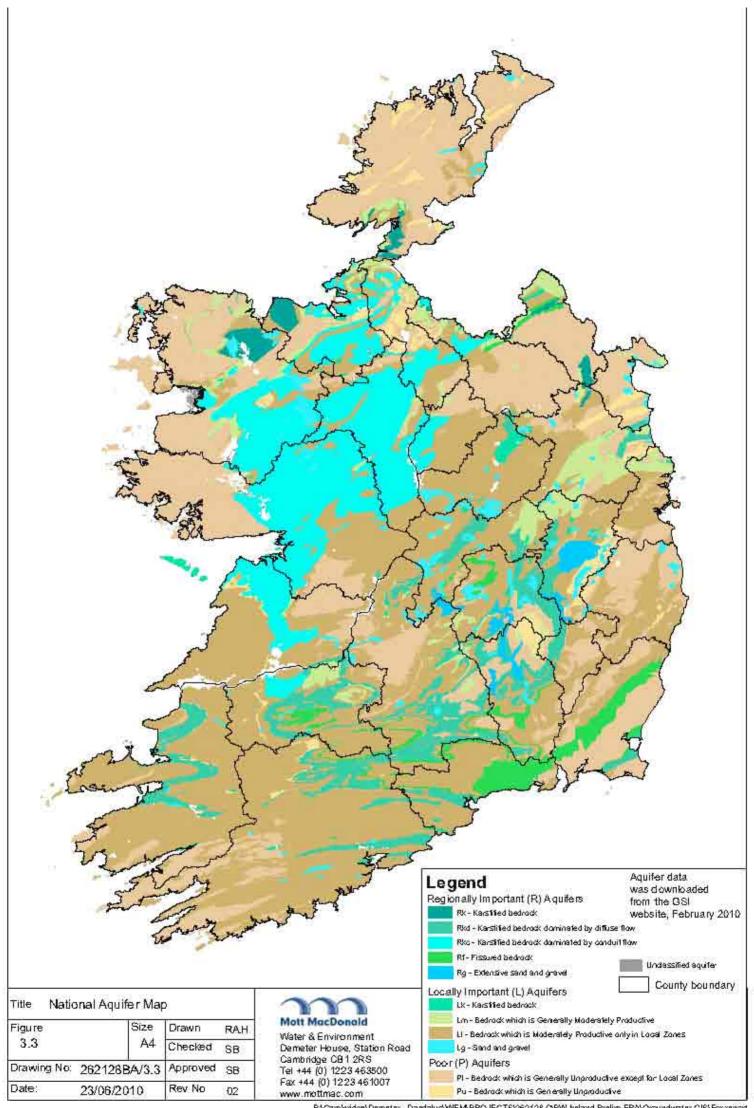
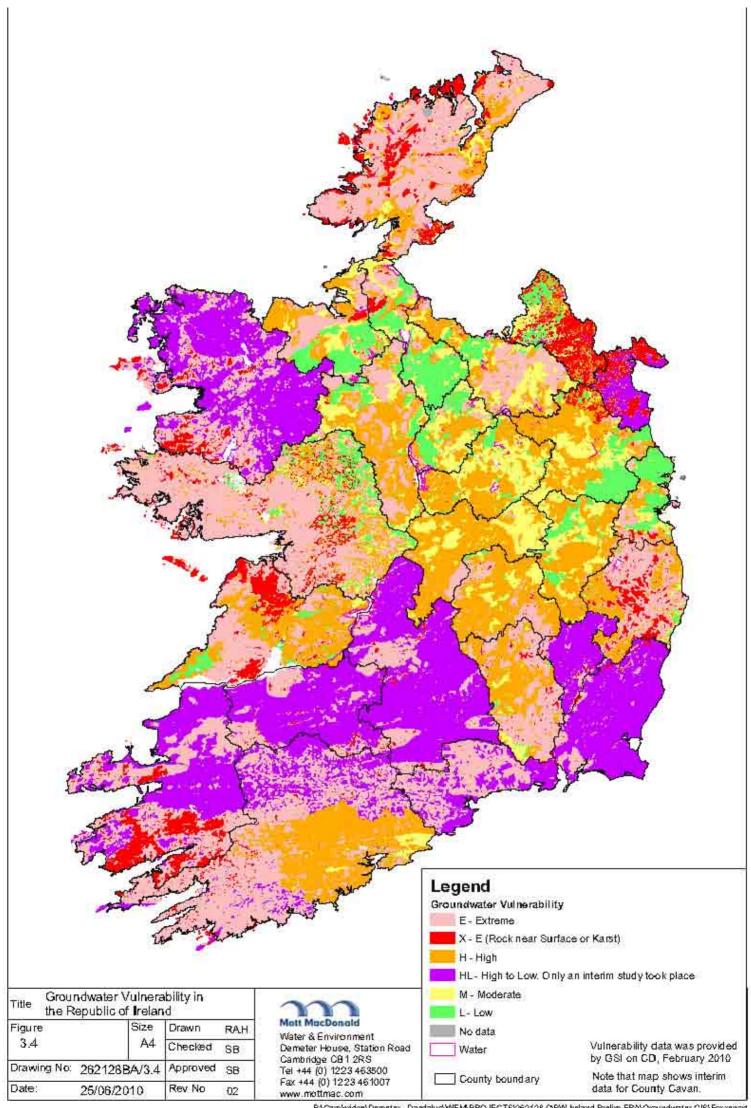
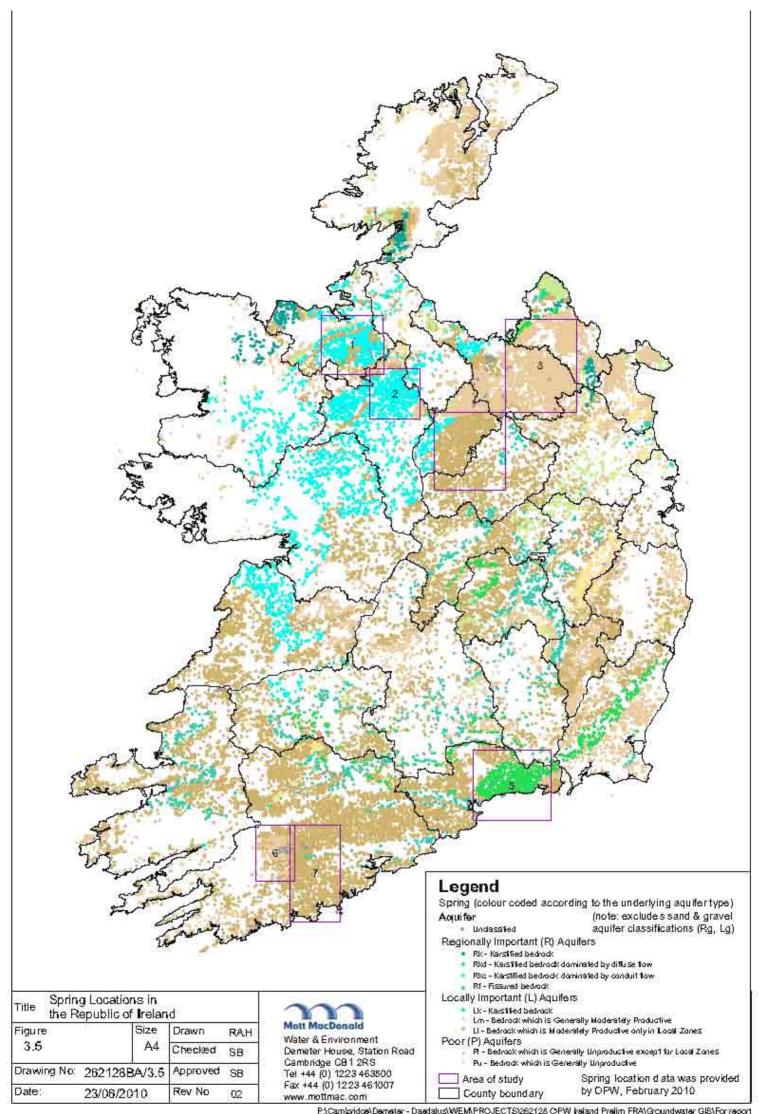


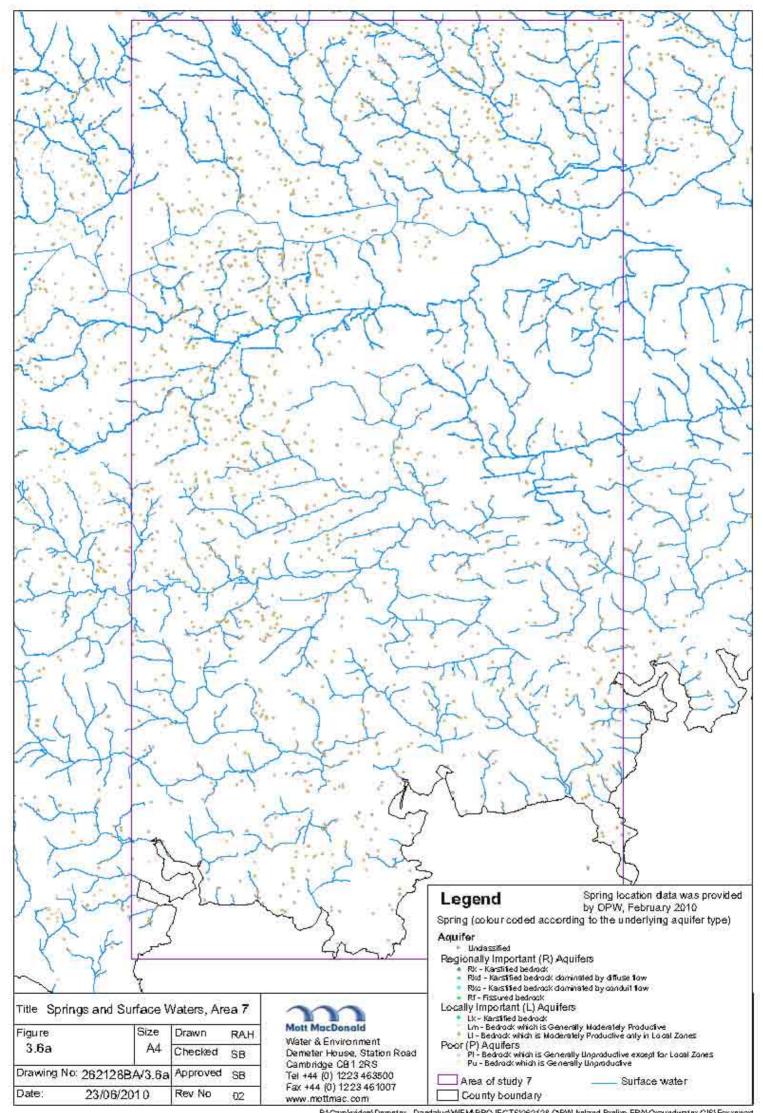
Figure 3.1 - Generalised Bedrock Map showing Rock Unit Groups

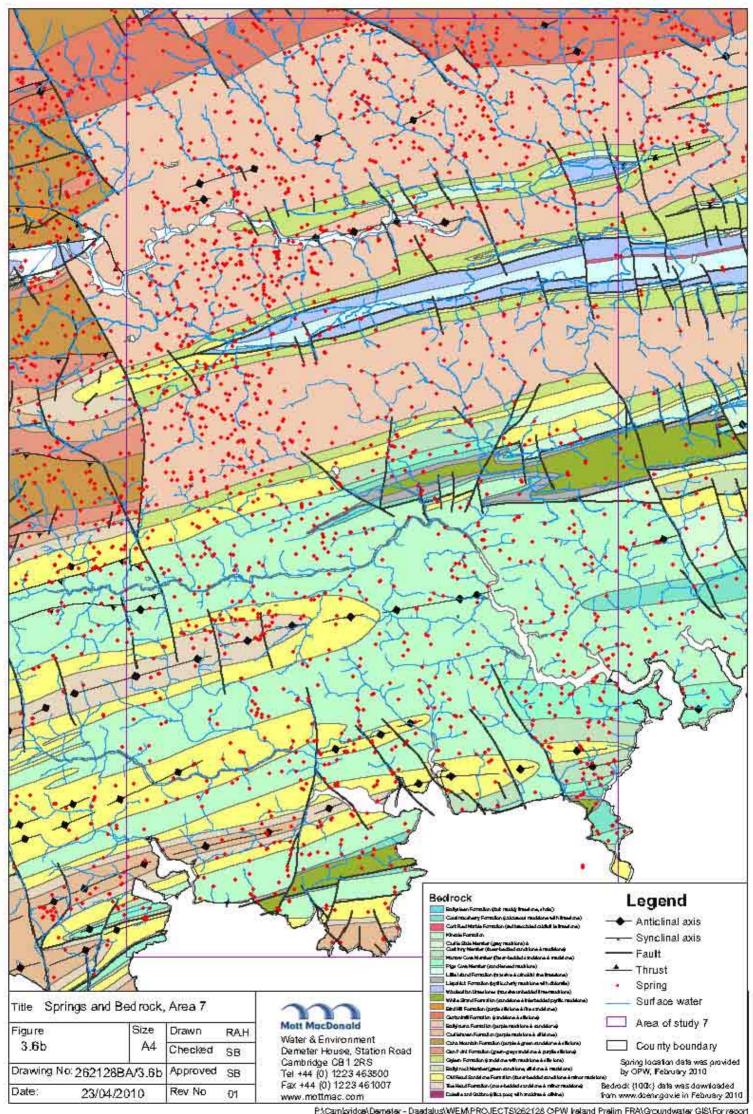


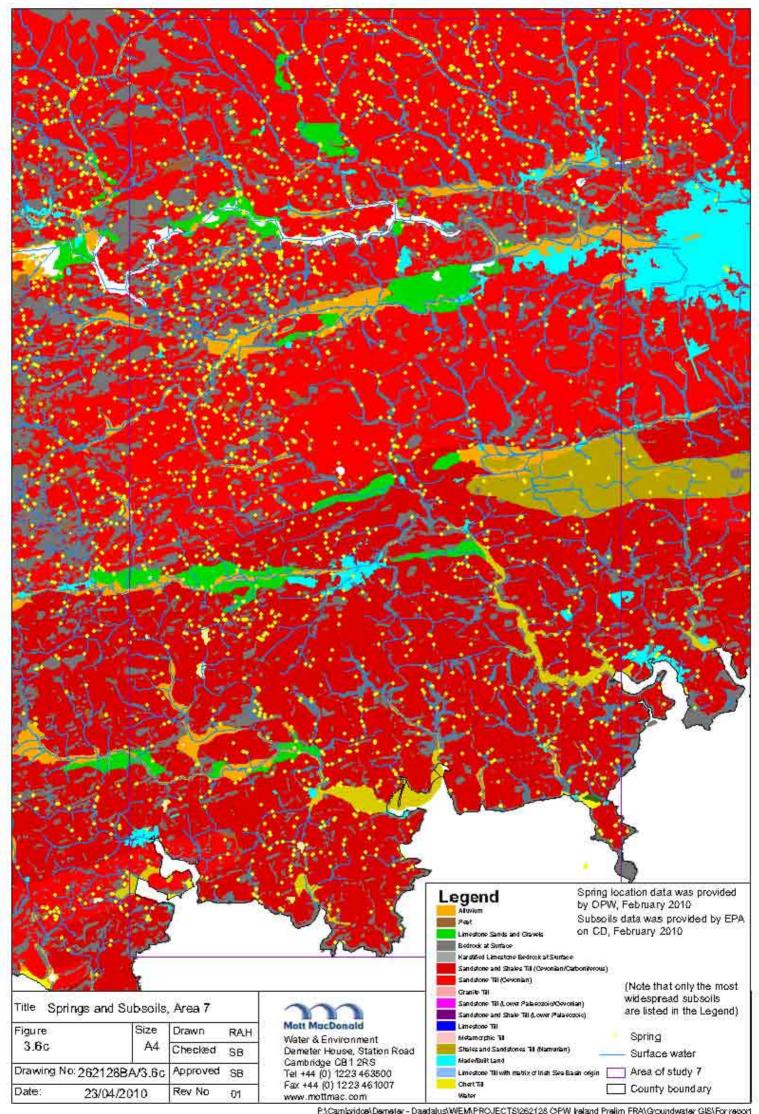














Groundwater Flooding in Europe

4.1 Occurrence of Groundwater Flooding

A literature survey of groundwater flooding in Europe was carried out at an early stage of the project in order to examine the responses of other European countries to meeting their obligations with respect to the Floods Directive. Literature in all the European languages was searched for. The literature survey is included in the list of references which follows Chapter 7.

The survey includes information previously made available to OPW, sources of information from the UK (principally publications relating to Defra's `Making Space for Water' consultation [Defra, 2005] and work carried out by the British Geological Survey (BGS)), and papers accessed through an internet search. Little information was found from outside the UK, despite the fact that hydrogeological environments in some countries would appear to be conducive to groundwater flooding.

The principal body of work was carried out by Jacobs for the Environment Agency (the Agency) as the competent authority for England and Wales reporting to Defra, and which formed the programme strand HA5 `groundwater flooding records collation, monitoring and risk assessment'.

An initial scoping study [Jacobs, 2004] provided detailed information on the scale, distribution, nature and mechanisms driving groundwater flooding in England. Volume 1 comprises a report, and Volume 2 is a series of maps showing the location of floods and base flow indices for river sections in each Agency area, and both regional and local groundwater emergence maps. Groundwater flooding is described as `the type of flooding that can be identified as being caused by water originating from beneath the ground surface from permeable strata through a natural process'. Emergence is defined as `the appearance of groundwater at the land surface or below the surface in sub-surface structures such as excavations, cellars, communication conduits and tunnels'. Also, `groundwater flooding can also be differentiated from surface water flooding by its persistence, with a typical duration that is measured in weeks rather than hours and days and has a tendency to occur throughout the winter, often extending into spring and sometimes into the early summer'.

The scoping study [Jacobs, 2004] commenced with the collation of all documented groundwater flood events. The hydrogeological environments where these events occurred were then examined and the flooding mechanisms established. These initial phases of work were revisited [Jacobs, 2007] when the risk of groundwater flooding with respect to all the main bedrock aquifer types in the UK was examined in more detail. It was concluded that there was very little or no conclusive evidence of flooding associated with the Permo-Triassic Sandstones, the Jurassic Lower Greensands and Limestones, the Magnesian Limestones, and the Carboniferous Limestones. The only bedrock aquifer where significant flood events occur is the Chalk of south and east England.

An extended report [Jacobs, 2006] focussed on flooding associated with Chalk aquifers, and the final consolidated report [Jacobs, 2007] gave details of all aspects of programme strand HA5. Jacobs [2007] identified three groundwater environments (referred to as sources) where flooding is a particular risk:

- Groundwater level rise in response to prolonged extreme rainfall which occurs predominantly
 on the Chalk aquifer. Flooding can either occur recurrently at several locations or less frequently on
 a significant geographical scale.
- Groundwater level rise on floodplains in response to high in-bank river levels also has a
 potentially large geographical distribution and can cause significant social and financial impact,



particularly to basements of structures located close to rivers. Although these areas may fall within fluvial and coastal flood envelopes, impacts resulting from this form of groundwater flooding could be overlooked in the planning process.

• Groundwater diversion by artificial obstructions and pathways can occur in sufficient density in some areas (for example, west of London) to contribute to significant rises in groundwater level.

The first two mechanisms are described in more detail by MacDonald [2009], as outlined in Box 4.1.

Box 4.1: Groundwater Flooding Mechanisms (after MacDonald, 2009)

Groundwater level rise in response to prolonged extreme rainfall only occurs in unconfined aquifers, primarily the Chalk of south and east England, and generally in upper reaches of Chalk catchments in localised low lying areas due to upstream extension of stream sources and the emergence of rarely activated springs. The response to prolonged extreme rainfall is coupled with above average antecedent groundwater levels. Flooding may occur a few days or several weeks after a major recharge event and often lasts for weeks. During periods of rapid recharge, the low storage fissure system in the Chalk aquifer takes up the majority of the recharge causing a rapid rise in groundwater levels. The rise is larger away from valley bottoms where the fissure network is less developed. Tens of metres of rise can occur during periods of extreme recharge. The low or moderate permeability of the Chalk aquifer away from valley bottoms means that high groundwater levels do not readily dissipate. Furthermore, groundwater released from the Chalk matrix slows the recession after the peak water level has passed. Examples: upstream of permanent River Pang, Hampshire; Patcham area of Brighton, Sussex.

Groundwater level rise on floodplains in response to high in-bank river levels is relatively common compared with flooding in unconfined aquifers (see above). Flooding occurs when water moves laterally out through the permeable sides of a river channel into lower lying alluvial deposits that overlie relatively impermeable bedrock. The mechanism often precedes fluvial (overbank) flooding, particularly where engineering measures have allowed high in-bank river levels. It is more likely in area of relatively narrow floodplains and is complicated by urban drainage and man-made structures. The floods are relatively short-lived as the high permeability of the deposits allows groundwater to drain once river levels fall. **Example**: low lying areas of Oxford city.

4.2 Mapping Groundwater Flooding

The mapping of groundwater flooding commenced in about 2004 when it was recognised that such flooding is a hazard that had been largely ignored in the past. The literature survey suggests that various organisations in the UK were at the forefront of the work. Indeed, no literature could be found detailing mapping methods in use elsewhere in Europe. Eximap's handbook on good practices for flood mapping in Europe [Eximap, 2007] does consider groundwater flooding, but only in passing, as a specific case and then with respect to the three main approaches developed in the UK.

The three approaches to the mapping of groundwater flooding in the UK are described below.

4.2.1 Groundwater Emergence Maps

Groundwater emergence maps (GEMs) involve simulating a groundwater surface rise to intersect the ground surface and encompass known locations of groundwater flooding. The approach [Jacobs, 2004] is based on contours of groundwater level elevation (mAOD) provided by the Agency and the BGS converted to contours of depth (mBGL) using a digital terrain model (DTM) of ground level contours at 2 m intervals. There are various limitations to this approach, particularly the difficulty in raising the groundwater level



surface by realistic amounts throughout the area of flooding, and the fact that the DTM contour interval is relatively coarse. However, the approach does give a general indication of areas where groundwater flooding is a hazard. The maps do not show risk.

Examples of GEMs can be found in Jacobs [2004, 2007] and Morris et al [2007]. A typical GEM for an area on the north bank of the River Thames at Rainham Marshes is given in JBA [2007].

4.2.2 Groundwater Flood Susceptibility Maps

Groundwater flood susceptibility maps (GFSMs) were developed by the BGS in response to an increasing awareness of the potential hazard of groundwater flooding [Jackson 2004, McKenzie et al 2005]. The maps identify areas where groundwater is close to the ground surface and where hydrogeological conditions suggest susceptibility to groundwater flooding. Unlike GEMs, the maps do not identify or delineate the flooding hazards themselves, rather they show whether these are likely or not. The approach does not map the risk of flooding.

The maps now cover all aquifers in England, Wales and Scotland (*pers.comm*, A.McKenzie). Input datasets include a permeability index, digital elevation data, and rest water levels. Estimates of confidence in the input datasets are included in the mapping process. The BGS has more confidence in the maps for some aquifers (for example, the Chalk and permeable subsoils with good hydraulic connection to surface water courses) than others. The output comprises maps of flood susceptibility (with five classes of groundwater levels as depths below ground, ranging from <2.0 m to >10.0 m) and corresponding maps of confidence (with five classes ranging from low to high). The depths are nominal rather than real because they are a combination of observed and modelled values and incorporate estimates of likely seasonal variations.

4.2.3 Groundwater Flood Risk Maps

Groundwater flood risk maps are based on the analysis of groundwater level data at observation boreholes. The analysis examines the return periods of particular groundwater levels and calculates corresponding annual exceedance probabilities. The levels are then used to define groundwater surfaces which, combined with ground elevations, indicate areas at corresponding risks of flooding. The approach has been used by Zaidman et al [2008] and Experian [2008].

This is the only approach that maps the risk of groundwater flooding. There are difficulties inherent in the approach. The two principal difficulties are:

- At least 30 years of observed water levels are required and more than 50 years are preferred in order to provide reasonable confidence in the return periods identified; there are few observation boreholes with this amount of data.
- The areal coverage of observation boreholes is generally sparse; variations in groundwater levels must be inferred within many areas of interest.



Occurrence of Groundwater Flooding in the Republic of Ireland

5.1 Background

5.1.1 Hydrogeological Environments and Flooding Mechanisms

A robust assessment of groundwater flooding in the Republic of Ireland requires an evidence-based understanding of the hydrogeological environments where flooding mechanisms may, or do, occur. Both positive evidence (the known occurrence of floods) and negative evidence (the known absence of floods) must be considered.

Use has been made of a wide range of background information, including reports on flooding in karstic limestone environments referred to in discussions with experts at GSI and TCD. These discussions have also yielded a significant quantity of unpublished information and photographs, principally from P Johnston of TCD who has been engaged for some years on a study of turloughs, and GSI hydrogeologists who have provided various draft documents and the latest versions of their databases.

The following sources of evidence have been interrogated:

- databases: www.floodmaps.ie (for flooding associated with turloughs); www.epa.ie (for gauged surface water flows); spring locations defined by the OSI obtained by OPW; and observed groundwater levels provided by EPA
- information on geology, subsoils, karst features, turloughs, aquifer vulnerability, and groundwater bodies downloaded from www.gsi.ie or provided via email and on disk by GSI
- satellite and aerial photograph imagery, DTM tiles, and rainfall quantities provided by OPW
- aerial photographs and historic maps for selected locations in the eastern half of the country, viewed on http://maps.osi.ie.

The evidence indicates that the principal hydrogeological characteristics of **bedrock aquifers** which together control whether or not groundwater flooding has the potential to occur are:

- low or very low aquifer storage and
- high transmissivity.

The flooding mechanism involves a rapid rise in groundwater levels to, or close to, the ground surface in response to exceptional and sometimes prolonged recharge. This rapid rise in groundwater levels is due to the very low void space available to accept the recharge, along with the inability of groundwater to flow away from areas of recharge sufficiently quickly. This mechanism is the same as that described by Jacobs [2004, 2006] for the Chalk aquifer in England. There is strong evidence that this is the principal mechanism that causes groundwater flooding in the Republic of Ireland.

The principal hydrogeological environment of **subsoil aquifers** where groundwater flooding has the potential to occur is that of floodplains where permeable deposits are in hydraulic continuity with adjacent rivers. The flooding mechanism involves the movement of river water outwards into the aquifer and a resultant rise in groundwater levels. This mechanism is the same as that in similar environments in the UK, except that in the UK these are underlain by relatively impermeable bedrock. Although the hydrogeological environment exists in the Republic of Ireland, there is no evidence of any associated groundwater flooding.



Several other hydrogeological environments and mechanisms described by Jacobs [2004, 2007] have been examined in the context of groundwater flooding in the Republic of Ireland. However, no evidence has been found of any groundwater flood events that could be attributed to these.

It is important that fluvial and pluvial flooding is not confused with groundwater flooding. Examples of the former are:

- over-bank flooding by river water due to an increase in the amount of groundwater baseflow
- blocked swallow holes, estavelles, etc. preventing surface runoff from moving into the subsurface
- increased spring flows that cause surface water flooding downstream of the springs.

5.1.2 Groundwater Flooding Potential of Irish Aquifers

The potential of Irish aquifers to flood is referred to in GSI [2009 (draft)] and included in a draft document authored by experts at GSI. The latter has been incorporated into a summary (Appendix D) which includes all the available evidence and describes the relationships between aquifer categories, the mechanisms for groundwater flooding and the floods themselves. The following aquifer categories were considered by GSI:

- regionally important karstified aquifers Rk, Rk^c and Rk^d
- regionally and locally important fissured bedrock aquifers Rf and Lm
- regionally and locally important sand and gravel aquifers Rg and Lg
- locally important and poor aquifers LI, PI and Pu.

With one possible exception (the Ballysteen Limestone), the only categories for which there is any **positive** evidence of extensive groundwater flooding are the regionally important karstified aquifers Rk, Rk^c and Rk^d. These are discussed separately in Section 5.2.

Areas underlain by most **fissured bedrock aquifers** (Rf and Lm) are **not prone to flooding** because the aquifers typically have sufficient storage and transmissivity to mitigate prolonged and intense rainfall. However, in very low-lying areas the water table may be so close to ground level that groundwater could impact on buried structures and services. These areas are relatively small so that if such flooding occurred it would be at a local scale. There is no written or verbal evidence that this has ever happened. The one possible exception to this is the **Ballysteen Limestone** in the south which is classed as a fissured bedrock aquifer although it is associated with 13 turloughs (see Section 5.1.3 below).

Areas underlain by sand and gravel aquifers (Rg and Lg) are also not prone to groundwater flooding. This is because the aquifers have very large storage capacities due to their high porosities. The only known detailed study of potential groundwater flooding investigated the sand and gravel aquifer associated with the Lee River (north and south) in Cork City [Halcrow 2007]. No evidence of groundwater flooding was found, although it was recognised that this could potentially occur, most probably through the hydraulic transfer of pressure waves caused by high tides. Also, Tedd et al [2010] reviewed groundwater levels in the aquifers of the SERBD, and general hydrogeological characteristics are described in summaries of groundwater bodies, such as those for the Barrow Valley Sand and Gravel and the Kilmanagh Sand and Gravel. There is no evidence of flooding, despite the fact that groundwater levels are often within about 2 m of the ground surface. However, in very low-lying areas the water table may be sufficiently close to ground level that groundwater could impact on buried structures and services. A special case is that of coastal / estuarine sand and gravel aquifers in hydraulic continuity with the sea, since an increase in



elevation of the mean sea level would impact on the elevation of the water table. Therefore, groundwater flooding of basements could potentially occur as a result of sea level change.

Locally important and poor aquifers (LI, PI and Pu) mostly occupy upland areas where prolonged and intense rainfall tends to run off the land surface rather than being absorbed into the subsurface. In low-lying areas the water table is generally near ground level, especially in winter when the aquifer's limited porosity and permeability may lead to water logging. These areas of water logging are generally small and are covered by subsoils that have the same poor aquifer properties as the underlying rocks. They are often associated with surface water flooding and distinguishing between the two forms of flooding is difficult.

The potential of **subsoils** to flood has not been considered by GSI other than with respect to the sand and gravel aquifers. However, subsoils form an extensive and thick cover over much of the Republic of Ireland and, although individual deposits are not extensive, they could be of local significance with respect to groundwater flooding. This is a very different situation compared with that in the UK where bedrock outcrops over a much greater proportion of the landmass. Therefore, the potential of subsoils to flood is more significant in the Republic than in the UK. Also, there are numerous springs scattered across the country, many of which may originate in subsoils rather than the underlying bedrock, and groundwater levels in subsoils adjacent to surface waters may be relatively shallow. Despite this, there is no real evidence that groundwater flooding is associated with either springs or shallow groundwater levels associated with subsoils (see Section 3.7 for more details).

5.1.3 Turloughs as Evidence of Groundwater Flooding

Further evidence of the relationship between aquifer categories and groundwater flooding comes from the analysis of flood events and an examination of the hydrogeology of turloughs. Turloughs (meaning `dry lakes' in Irish) are unique to Ireland. They are seasonal, temporary lakes that form when groundwater from underlying limestone aquifers rises to the surface as groundwater heads rise and become dry as the heads fall. By definition, turloughs are groundwater floods. However, under exceptional conditions the turloughs expand beyond their normal seasonal extents and then appear more flooded than normal.

Information on over 5000 flood events is held by the OPW on www.floodmaps.ie [Adamson, 2009]. Interrogation of the database by OPW gave 364 events that mention groundwater. Examination of a selection of these events indicates that for most there is no information other than a name and a general

location. A few are mistaken entries. This leaves 37 events for which there are reports containing details of the flooding. All are associated with turloughs. There are 482 turloughs on GSI's most recent database. The 364 flood events and the 482 turloughs are located on Figure 5.1 and the turloughs are summarised according to RUGs and aquifer categories in the accompanying box. The overwhelming majority of turloughs are in the west and north-west on

Book Unit Croup	Aquifer	Number of
Rock Unit Group	Category	Turloughs
Pure Bedded Limestones	Rk ^c	438
Upper Impure Limestones	Rk^d	15
Lower Impure Limestones (Ballysteen Limestone)	Rf	13
Pure Unbedded Limestones	Rk	10
On boundaries between groups	1	6

the Pure Bedded Limestones RUG. This is a regionally important karstified aquifer dominated by conduit flow (Rk°). Turloughs are, by definition and by their mode of occurrence, karstic features and it is merely a matter of classification that has assigned the Ballysteen Limestone to the fissure flow dominated aquifer category since this is its dominant flow type.



5.2 Groundwater Flooding and Regionally Important Karstified Aquifers

The available evidence supports the conclusion that the only groundwater floods of significance in the Republic of Ireland are those associated with regionally important karstified aquifers and that most occur on Pure Bedded Limestones. However, there are real differences in the nature of the flooding across the country. These differences reflect both the variations in the hydrogeological environment of the aquifers and the distribution of rainfall. Three broad regions of flooding have been identified for the purpose of this project:

- Lowland karst of the western lowlands in Counties Clare, Galway, southern Mayo and small parts
 of other counties.
- Upland karst in County Roscommon and parts of Counties Clare, Limerick, Galway, Mayo, Sligo, Leitrim and Offaly (west, north-west and locally in midlands).
- Other karst in the south and south-east and parts of the north-east.

The three regions of groundwater flooding are described below.

5.2.1 Lowland Karst Region of the Western Lowlands

5.2.1.1 Introduction

Groundwater flooding is particular prevalent in the lowland karst of the western lowlands. This region extends from the area of the River Fergus in County Clare, north-east to the turlough system near Gort in County Galway, and further north to the area east of Loughs Mask and Corrib in County Galway and southern County Mayo. The region is typically flat-lying or gently undulating, and ranges in altitude from sea level to about 150 mAOD. The karstic landscape is formed predominantly on Pure Bedded Limestones. The bedrock is often exposed at the ground surface since there is generally no thick cover of subsoils.

The natural karstic drainage system comprises a complex network of swallow holes, dolines, shallow depressions and estavelles where surface water sinks into an underground environment in which groundwater moves swiftly through fissures, conduits and caves under a regional, rather than local, hydraulic gradient [Drew and Daly 1993, Ball et al 2000, Drew 2008]. The groundwater eventually emerges as springs or as baseflow in rivers. Most of these have small discharges but the most famous, at Kinvara and Cong, have huge discharges of up to 2580 Ml/d. At times of high recharge, and possibly driven by a surcharging mechanism in conduits, groundwater rises to the ground surface and forms turloughs.

The natural drainage system has been modified in many areas by the construction of artificial drainage channels which were designed to alleviate flooding but which have partially deactivated large areas of the karstic system by imposing artificial river networks on areas that were naturally drained via karst [Drew, 2008]. The Rivers Clare, Robe, Abbert and Dunkellin in Counties Mayo and Galway are examples of channelised rivers.

Further south, there is less artificial drainage. Consequently, the surface expression of the karstic drainage system is manifested in the presence of numerous turloughs. There are two broad contiguous areas of turloughs: the Blackrock to Coy, Pollaleen, Polltoophill and Coole branch and the Cutra to Mannagh to Hawkhill to Coole branch into Lough Caherglassaun near Gort; and the south-west to north-east belt between the River Fergus and Lough Bunny south-west of Gort. It is noted that some of these turloughs, such as Coole, Caherglassaun and Bunny, are in fact permanent water bodies and not true turloughs.



5.2.1.2 Turlough System near Gort

Groundwater flooding of the turlough system near Gort has been well documented since the early 1970s (see Mac Dermot [1991 and 1995] and Daly [1992 and 1993]). The extreme flood event in late 1994 to early 1995 prompted a major study [Southern Water Global, 1997] for the OPW. The extreme event in late 2009 is documented with photographic evidence, data downloaded from loggers installed in the turloughs at Blackrock and Lough Coy, and commentary provided by P Johnston and others at TCD.

The movement of groundwater through the system is complex. For example, although only two branches are named above, Southern Water Global [1997] identified nine separate flow routes. However, the system basically comprises the westerly drainage of water originating on the relatively impermeable uplands of Slieve Aughty.

The flood event in late 2009 proceeded as follows:

- An extreme amount of rain fell over a relatively short period in western Ireland during the third week
 of November.
- 2. Average daily water levels of the River Fergus at the Ballycorey gauging station (ID 27002, at Irish National Grid (ING) 134431 180323) rose from 9.10 m on 18/11/09 to a peak of 9.78 m on 24/11/09 and then fell back to 8.97 m by 06/12/09 (the peak level on 24/11/09 is the highest ever recorded at the gauging station).
- 3. Groundwater levels in turloughs rose in response to extreme recharge. Peak levels progressively lagged behind the peak surface water flood between the upstream turlough at Blackrock and the downstream turlough at Caherglassaun. Whereas the groundwater peak at Blackrock may have occurred on 24/11/09 or 25/11/09, the peak at Caherglassaun was probably about nine days later, on 03/12/09 or 04/12/09.

The evidence includes photographs of floods taken at various locations:

- Hawkhill road junction near Caherglassaun (ING 140978 202108) on 24/11/09 and 02/12/09
- A house near Caherglassaun (ING 141895 206422) on 02/12/09
- Blackrock Farmhouse (ING 149586 207623) on 24/11/09
- Blackrock butcher's house (ING 150028 207797) on 24/11/09
- Two other places at Blackrock on 24/11/09 (ING 150028 207797, 149817 207472)
- Ternon house (ING 141787 197358) on 24/11/09
- Ballylee Road (ING 148229 206228) on 24/11/09
- Newtown Causeway (ING 143321 201907) on 24/11/09
- Thor Ballylee Tower near Pollaleen turlough (at ING 148144 206084) on 24/11/09.
- 4. High groundwater levels in the turloughs were maintained for up to two weeks in places as the flood wave was constrained by the limiting capacity of the coastal discharge system at Kinvara. Thereafter, levels gradually fell back to their more normal winter levels.

A comparison of flood levels shown on photographs taken at Blackrock and at Thor Ballylee Tower in late 2009 and early 1995 indicates that the two flood events had similar maximum levels at the upstream turloughs (principally Blackrock, Coy, Pollaleen and Polltoophill). The levels shown on photographs taken near Caherglassaun indicate that the flood in late 2009 became progressively higher than that in early 1995 down hydraulic gradient in the conduit system, amounting to a difference of 0.7 m at Caherglassaun. This can be explained by extra runoff from the south side of the Slieve Aughty hills passing through Coole.



The maximum flood level on the tower wall at Thor Ballylee in late 2009 and in early 1995 was about 18.0 mAOD (3.0 m above the adjacent road, which has a ground elevation of about 15.0 mAOD). The maximum flood levels as recorded by loggers at Blackrock and Lough Coy in late 2009 were 29.3 mAOD and 19.3 mAOD respectively. The large difference in levels of 10 m between the adjacent turloughs of Blackrock and Lough Coy reflects the latter's more constrained connection to the conduit system.

5.2.1.3 Karstic System between the River Fergus and Lough Bunny

Groundwater flooding of the area between the River Fergus and Lough Bunny has not been so well studied as that near Gort.

The initial characterisation of the Ennis groundwater body (see www.gsi.ie) is a good source of hydrogeological information and P Johnston has provided a useful background to groundwater flooding in the region and the nature of the turloughs.

While the bedrock underlying the region south-west of Gort is also Pure Bedded Limestone, the landscape is rather different from that to the north-east. There are more streams, more permanent lakes (such as Loughs Bunny and Muckanagh) and far fewer turloughs. At least some of the permanent lakes are mostly groundwater and their water levels are therefore controlled by the same mechanism that controls levels in turloughs. It is probable that the bedrock is less well karstified near ground level, resulting in shallow depressions filled by fen-like wetlands that may contain surface water, groundwater or a combination of the two. However, two deeper levels of karstification controlling groundwater movement at depth are suspected.

Lough Bunny is on the watershed between the River Fergus to the south-west and the turlough system near Gort to the north-east. A conduit system connects Lough Bunny to Clonteen and Hawkhill from where groundwater moves to Lough Coole or directly to Kinvara. Castle and North Ternon Loughs drain underground through Lough Bunny to the north-east. The rest of the area, including South Ternon and Muckanagh Loughs drains towards the south-west into the River Fergus system. However, the probable existence of two levels of karstification means that groundwater flow directions are complex and may change depending on groundwater levels.

Notwithstanding the complex karstic drainage system south-west of Gort, it is the case that groundwater flooding is known to occur, both at genuine turloughs (such as the Castle and the Ternon Loughs), and at permanent lakes (referred to as "turloughs" in later sections of this report). For the purpose of mapping the extent of these floods, it is assumed that the event in late 2009 was no more severe than that in early 1995.

5.2.2 Upland Karst Region (West, North-West and Locally in Midlands)

The upland karst region is defined by its altitude, which generally ranges between 100 mAOD and 300 mAOD, and its geomorphology; valleys tend to be incised and hills are steep-sided. The karstic landscape is formed predominantly on Pure Bedded Limestones and the aquifer is dominated by conduit flow. Subsoils are thin, sparse or absent at higher elevations [Tynan et al 2006, Drew 2008] but form a more extensive cover at lower elevations. Turloughs are less common than in the western lowlands (see Figure 5.1) and some other karstic features, such as caves, are also less common. There any many dry valleys south of Roscommon.

The natural karstic drainage system comprises a complex network of swallow holes, enclosed depressions, and occasional estavelles where surface water sinks into an underground environment dominated by



conduit flow. Far fewer tracer tests have been carried out in the upland karst region than in the western lowlands and consequently the details of groundwater flow are much less well known. However, spring flows are generally large, hydraulic gradients are typically an order of magnitude higher than those in the western lowlands, and groundwater flow paths are kilometres long [Drew, 2008].

Groundwater flooding in the upland karst region occurs, but is much less common and much less extensive than in the western lowlands. This is principally because there are fewer turloughs, hydraulic gradients are steeper, and the ground surface is less flat. Also, such flooding as does occur is less well documented.

5.2.3 Other Karst Region (South, South-East and Parts of North-East)

The third region of karstified limestones encompasses the rest of the country and comprises all the occurrences of karstified aquifer categories apart from bedrock aquifers dominated by conduit flow. Occurrences are local and scattered across the country.

Karstification is much less well developed than in the other two regions. This is reflected in the relative absence of known turloughs; GSI's database contains fewer than 40 turloughs in this region and most of the database entries for these turloughs give no information apart from names and approximate locations.

5.3 Groundwater Flooding Severity

The scope of work for the first phase of this project includes an assessment of the extent and scale of the groundwater flooding hazard across the Republic of Ireland. Although a consideration of flooding risk is not part of the scope, it is important to understand the severity of the flooding hazard in order to inform the next phase of work which will identify receptors and define risks and consequences.

As explained in Section 5.2.1, the groundwater floods near Gort are a recurring hazard that is well documented. An assessment of the flood in late 2009 indicates that it was as severe as the previous flood in 1994 – 1995 over most of its extent but somewhat more severe around the downstream turlough at Caherglassaun. Southern Water Global [1997] examined the relationship between rainfall, as measured at the Gort Derrybrien rain gauge, and flood severity and concluded that severe flooding occurs in years when the mean rainfall between December and February exceeds 550 mm. This happened in 1958 – 1959, 1989 – 1990, 1993 – 1994 and 1994 – 1995 (when a maximum of 870 mm was recorded). Southern Water Global [1997] also noted an increase in the total winter rainfall since records began in 1941 and showed that this is caused by an increase in the rainfall intensity on wet days rather than an increase in the number of wet days.

Rainfall and gauged surface water flows provided by OPW have been examined for this project in order to assess the nationwide severity of the recent groundwater flooding and to corroborate and update the findings of Southern Water Global [1997]. This assumes that both rainfall and surface water flows are valid indicators of groundwater flows. In fact, there are many variables that affect the timing and quantity of peak surface water flows. These include catchment size, nature of substrate including acceptance of recharge, permeability and thickness, rainfall distribution, and antecedent conditions. The presence of large sand and gravel bodies, particularly in the east and south-east, can also have a buffering effect on river flood levels because of their large storage potential and relatively slow baseflow response time.

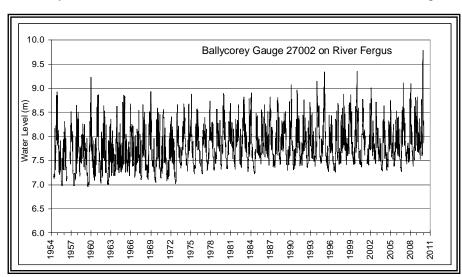
Rainfall data from a number of gauges across the country were provided by OPW. The data records have not been updated beyond 2006. Severe groundwater flooding has occurred since 2006 and therefore the records are of limited use.



Average daily water levels at a nationwide selection of river gauging stations were downloaded from the EPA's webpage hydronet.epa.ie. The dates when maxima occurred are shown on Figure 5.2. Dates in late 2009 are scattered across the country except in the area around Dublin. South of Dublin the maxima were on 16/01/10 and may reflect a continuation of the extreme event in late 2009. It is noteworthy that there are many locations where maxima were not in late 2009.

Average daily water levels at the Ballycorey gauging station (ID 27002, at 134431 180323) on the River Fergus were also provided by OPW. The data are assumed to be a good indicator of the amounts of groundwater flow through the karstic system of the western lowlands as the river lies within the region.

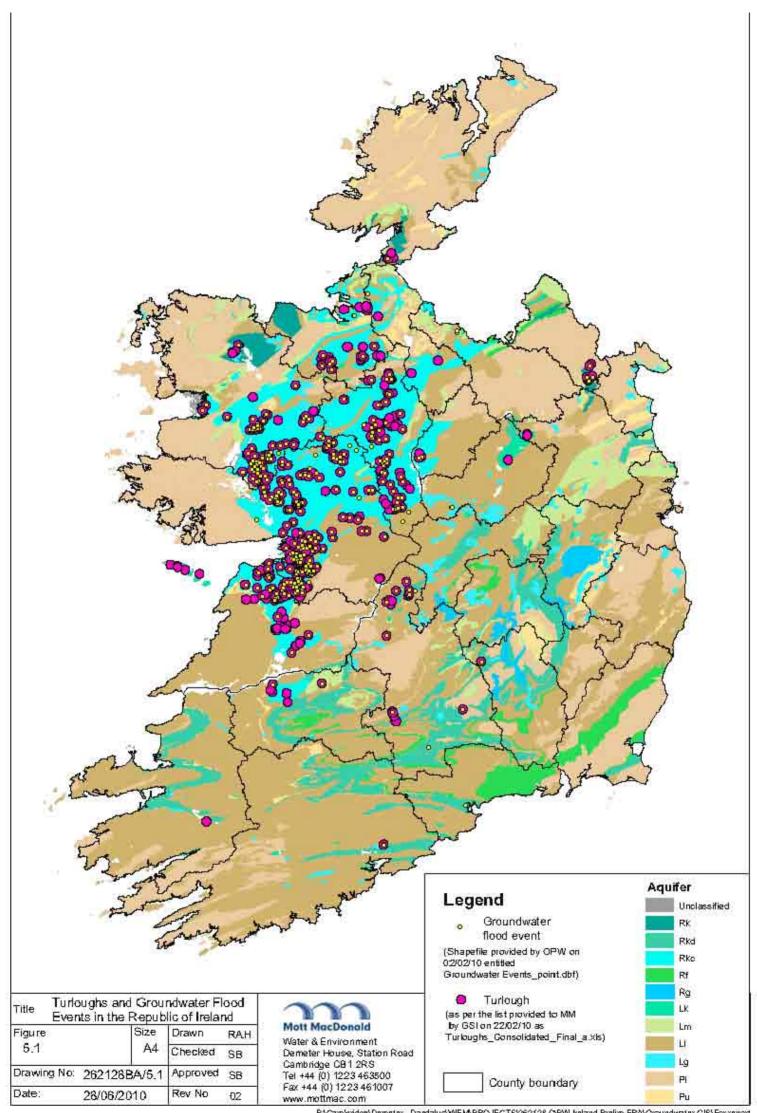
Levels from 1954 to early 2010 are summarised on the accompanying diagram. A gradual increase in the daily water levels appears to be occurring, although on closer inspection there is a stepped change in late 1972. This was probably caused by a and sudden permanent alteration in the channel immediately upstream of the gauge which has affected all subsequent readings. The maximum water level was in late 2009. Thus, data at the

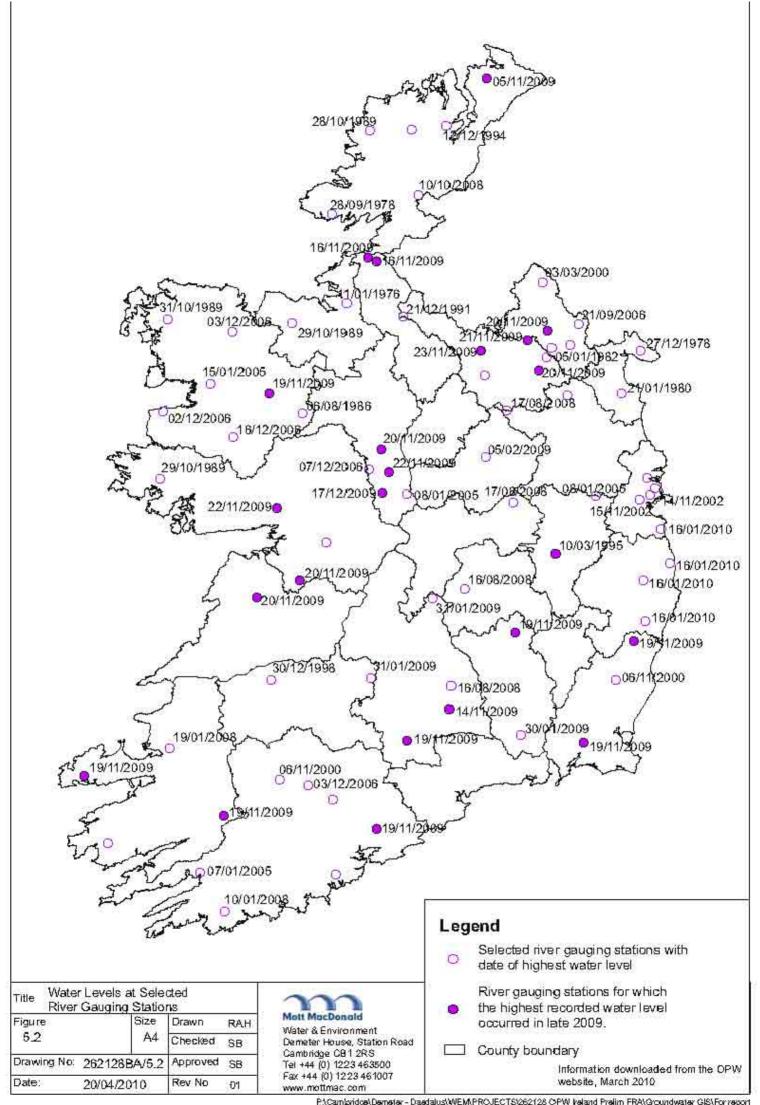


Ballycorey gauging station support other evidence that late 2009 was a time of extreme rainfall which resulted in extreme responses of flow systems in the western lowlands.

The evidence of Southern Water Global [1997] and from the Ballycorey gauging station indicates that the groundwater flood in late 2009 in the western lowlands was the most severe in about 50 years. However, seven of the nine levels above 9.0 m at the Ballycorey gauge have occurred on or after 1990. This supports the finding of Southern Water Global [1997] that severe groundwater floods have been more common since about 1990. It may be that climate change is having an effect and will have serious consequences with respect to the impact of flood hazards. Calculating a credible return period will be difficult because it will not simply be a matter of referring an event to the total length of the data record.

The possible impact of climate change on groundwater flooding has not been investigated any further for this project. However, it is noted that while some studies, for example Butler [2008], suggest that there will be no impact, others take the opposite view.







Mapping Groundwater Flooding in the Republic of Ireland

6.1 Introduction

An efficient, relatively simple but robust and scientifically justifiable methodology for mapping groundwater flooding has been developed for this project. It has been used to define the extents of groundwater floods around all the 482 turloughs held on GSI's most recent database and a few floods shown on digital images that are highly likely to be groundwater derived. The methodology comprises three inter-linked stages which differ from each other in terms of the availability of historic flood images, the amount and quality of existing information, and to regional variations in hydrogeology and potential recharge. Details of the methodology are given in Section 6.2 below.

The two principal types of maps of groundwater flooding hazards in the UK, namely GEMs and GFSMs, have not been applied to the Irish situation because both require detailed groundwater level data. As explained in Section 3.6, there are very few locations where groundwater level data are collected routinely and the records of these are of short durations that do not include the years when most of the severe groundwater floods have occurred. Furthermore, in karstic environments groundwater levels measured at one location may be unrepresentative of levels nearby and so are likely to be of limited value in the Irish situation.

The scoping document for this project [MM, January 2010] considered using areas of extreme and high vulnerability as surrogates for groundwater flooding. This approach was rejected after it became apparent that significant groundwater flooding only occurs at turloughs and, in any case, the approach is not possible due to the lack of groundwater level data in the extreme and high vulnerability areas.

An approach to complement the methodology for mapping flooding associated with turloughs was considered for the particular environment of springs and shallow groundwater levels close to surface waters. As explained in Section 3.7, there are about 50,000 mapped springs scattered across the country and there are many areas where groundwater levels are likely to be shallow. The mapping of areas encompassing springs and likely areas of shallow groundwater was rejected because there is no evidence that springs are a significant flooding hazard and the majority of their flow paths are short or very short. Also, there is virtually no data with which to accurately delineate areas of shallow groundwater.

6.2 The Methodology

The starting point was the examination of six ArcGIS images of floods provided by OPW. These images are of relatively small areas compared with the size of the Republic of Ireland and all are located in the west or north-west. Details are as follows:

- Image from aerial photography of flood in February 1990 for an area near Gort from Blackrock in the north-east, to Caherglassaun and Hawkhill in the west, and Lough Mannagh in the south-west (called Gort flood),
- image from aerial photography of flood in the winter of 1994 1995 for a more extensive area than that above including Blackrock in the north-east, to Caherglassaun and Hawkhill in the west, and Lough Mannagh in the south-west (called Gort Ardrahan flood),
- image from aerial photography of flood on 24/02/01 for a corridor along the River Shannon from Lough Bofin south to the northern two thirds of Lough Derg, including eastern areas of Counties Roscommon and Galway, north-western County Tipperary, and western County Offaly,



- satellite image of flood on 30/11/09 for the same area as that on 24/02/01,
- satellite image of flood on 02/12/09 for part of Lough Derg and eastern County Limerick,
- satellite image of flood on 04/12/09 for an area south-west of Gort from Lough Mannagh in the north-east to beyond the River Fergus in the south-west.

Stage 1 of the methodology (Section 6.2.1) is based on the flood images. It incorporates all the available information, including the evidence gathered during the severe flood in late 2009, and maps most of the groundwater floods in the western lowlands and the upland karst region.

Stage 2 (Section 6.2.2) is based on a statistical relationship between the base elevations of turloughs and associated groundwater flood levels shown on the available images. It has been used to map floods around turloughs outside the areas covered by the images. This stage includes the option to adjust the mapped outlines according to a set of realistic constraints, and sensitivity analysis.

Stage 3 (Section 6.2.3) is based on an examination of the reports of 37 flood events on www.floodmaps.ie that are identifiably groundwater and which have additional information other than just a name and location. The additional information has been used to adjust or corroborate flood outlines produced in Stages 1 and 2. This stage has been amended to include an examination of flood related features shown on aerial photographs and historic maps of the 24 turloughs located in the eastern half of the country. This has enabled a review of the flood outlines produced in Stage 2 to be carried out.

The actual delineation of most groundwater floods is based on topographic contours derived from DTM tiles provided by OPW. The contours are understood to be accurate to within \pm 0.70 m.

6.2.1 Stage 1: Mapping Groundwater Flooding in Western Lowlands and Upland Karst Region

6.2.1.1 Introduction

There are two distinctly different types of karstic drainage in the western lowlands and a third distinctive type in the upland karst region. Also, information on groundwater floods varies between the regions, from reports, data and numerical modelling results for the area near Gort in the western lowlands, to virtually no information in the upland karst region. These differences have influenced the mapping of groundwater floods in the three areas, as described in the separate sections below.

6.2.1.2 Mapping Flooding near Gort

The methodology for mapping the groundwater floods in the area near Gort is based on two images (those for February 1990 and the winter of 1994 – 1995) and photographic evidence, data downloaded from loggers installed in the turlough at Blackrock and at Lough Coy, and commentary provided by TCD for the severe flood event in late 2009. The flood map has evolved from an initial version prepared in April 2010, when the information for late 2009 was provisional, to the final version prepared in June 2010, after the information for late 2009 had been finalised.

In summary, the level of the groundwater flood in late 2009 was similar to that in 1994 – 1995 at Blackrock and at Thor Ballylee Tower, but increased progressively down hydraulic gradient so that it was (as confirmed after preparation of the initial map) about 0.70 m higher at Caherglassaun in late 2009 compared with in 1994 – 1995. The maximum level of the flood at Thor Ballylee Tower is estimated to have been



18.0 mAOD. There is a time lag of about nine days between the peak level at Blackrock on 24/11/09 or 25/11/09 and the peak level at Caherglassaun on 03/12/09 or 04/12/09.

For the initial version of the flood map, the 18 mAOD contour derived from DTM tiles was drawn and compared with the two images, as shown on Figure 6.1. The contour coincides with the outlines of the images near Thor Ballylee Tower but does not coincide elsewhere in the turlough system. It encloses too small an area up hydraulic gradient at Blackrock and too large an area down hydraulic gradient relative to the shapes. This is because it takes no account of the regional hydraulic gradient nor variations in ground elevations. Consequently, the initial flood map of the area near Gort was drawn to coincide with the outline of the flood image in the winter of 1994 – 1995, as shown in Figure 6.1.

The final version of the groundwater flood map incorporates photographic evidence and logged data of the flood extent in late 2009 at Blackrock, Lough Coy, Thor Ballylee Tower and Caherglassaun. Examples of the revised flood outlines for the final version of the map are given in Figure 6.2.

6.2.1.3 Mapping Flooding between the River Fergus and Lough Bunny

The methodology for mapping the groundwater floods in the area between the River Fergus and Lough Bunny uses one image (that for 04/12/09), and is based on advice from TCD relating to the flooding which occurred in late 2009. It is assumed that the extent of flooding in late 2009 was at a maximum on 04/12/09. This is reasonable, given the known characteristics of the event. The groundwater flood map of the area has been drawn to coincide with the outline of the image on 04/12/09.

There are more streams, more permanent groundwater fed lakes and far fewer turloughs in the area between the River Fergus and Lough Bunny than in the area near Gort. Groundwater flooding is known to occur, both at genuine turloughs and some permanent lakes. Images obviously cannot distinguish between groundwater and surface water floods. It was therefore necessary to decide whether individual floods shown on the image of 04/12/09 were groundwater or surface water derived. The decision was made that individual floods have the potential to be groundwater, with the exclusion of those distinguished by being located solely on peat and without an associated turlough on GSI's latest database.

The flood map for the western lowlands at completion of Stage 1 is shown in Figure 6.3.

6.2.1.4 Mapping Groundwater Flooding in Upland Karst Region

The methodology for mapping the groundwater floods in the upland karst region uses two images that cover the west and north-west (there are no available images for other areas, such as the Burren in County Clare). The two images were on 24/02/01 and 30/11/09 for a corridor along the River Shannon from Lough Bofin south to the northern two thirds of Lough Derg and including eastern areas of Counties Roscommon and Galway, north-western Country Tipperary and western County Offaly.

The flood event on 30/11/09 was more extreme than that on 24/02/01; there were more flooded areas between the rivers Suck and Shannon and more extensive flooding around Loughs Bofin, Ree and Derg in late 2009 compared with in early 2001. Also, flooding on both sides of the rivers occurred in late 2009 but not in early 2001. It is unlikely that the maximum extent of groundwater flooding in late 2009 coincided with the date of the image. Nonetheless, in the absence of other information, the satellite image of 30/11/09 is used to define the maximum extent of groundwater flooding in the region.



Since images cannot distinguish between groundwater and surface water floods, it was necessary to examine the hydrogeology of various flooded areas in order to decide whether these were groundwater or surface water derived.

Subsoils on both sides of the rivers Suck and Shannon are predominantly peat. Sand and gravel aquifers are not mapped, although there are local patches of alluvium. This indicates that the hydrogeological environment, in which the specific groundwater flooding mechanism associated with flood plains can operate, is not present. Therefore, it was assumed that the flooding in late 2009 on both sides of the rivers was surface water derived and not groundwater.

Most of the region covered by the image of 30/11/09 that lies outside the river valleys of the Suck and Shannon is underlain by karstified Pure Bedded Limestones in which conduit flow predominates. Limestone tills or peats overlie the bedrock except in a few patchy areas. The decision was made that any floods distinguished by being located solely on peat and not associated with a turlough were surface water derived. All other floods were assumed to be groundwater derived. Figure 6.4 illustrates this approach.

6.2.1.5 Discussion

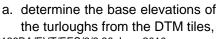
Permanent water bodies are present in all three areas mapped using Stage 1 of the methodology. Permanent water bodies in the centre of "turloughs" have been excluded from the groundwater flood map (the map around permanent water bodies has the appearance of rings). Also, if the outline of a "turlough" shown on an image coincides with that of the corresponding permanent water body then it too has been excluded. Examples of the latter include Loughs Bunny and Inchiquin. The permanent water bodies are those shown on the Teagasc subsoils map of Ireland provided by the EPA.

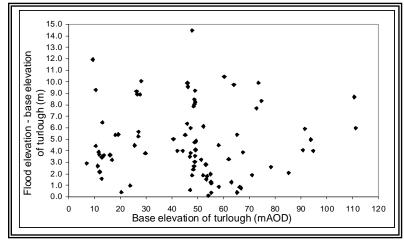
The final version of the map prepared under Stage 1 shows the extent of the most severe groundwater flood to have occurred in the area near Gort in the last 50 years or so. Maximum flooding in the other areas may not have occurred at the same time. Consequently, the map is not date specific and a return period for the most severe groundwater flood to have affected the other areas cannot be specified.

6.2.2 Stage 2: Mapping Groundwater Flooding in Areas Not Covered by Images

Flood images are not available for most of the Republic of Ireland. A methodology for mapping groundwater flooding throughout the country was therefore required for turloughs lying outside the area covered by the available images and for which there is little or no other information.

The methodology is based on an analysis of the differences between the base elevations of turloughs and the levels of the associated floods in areas covered by the images but outside the main turlough systems in the western lowlands. There are 85 such turloughs, the data for which are given in Appendix E. The analysis is summarised on the diagram and the analytical steps were as follows:







- b. determine the levels of the corresponding floods by matching contours on the DTM tiles with the flood outlines on the images,
- c. calculate the differences,
- d. assess the statistical relationship between the base elevations of the turloughs and the differences,
- e. determine the base elevations of all turloughs lying outside the images from the DTM tiles and use the statistical relationship to estimate the flood extents.

Differences between flood level and turlough base vary between 0.1 m and 14.5 m. It was anticipated that floods associated with turloughs located in relatively elevated areas would have greater differences than those associated with lower elevations; the scatter of data on the diagram proves that this is not the case.

There is probably a combination of reasons for the absence of a relationship between the two variables. Possible reasons are inaccurate DTM contours and flood extents at high elevations that are not maxima (ie. the image of 30/11/09 does not show the full extent of groundwater floods in the upland karst region).

In order to map groundwater flooding not covered by images it was decided to apply the median difference in elevations to all relevant turloughs. The median difference, calculated from the data in Appendix F, is 4.0 m. Therefore, the extent of individual floods was mapped by drawing round the contour 4.0 m above the base elevation of the associated turlough. Given the variability of the computed differences, realistic constraints were applied as follows:

- if the +4.0 m contour gave an unrealistically large flood then the contour closest to +4.0 m that gave a realistic size was followed instead,
- if two or more turloughs were located close together such that their +4.0 m contours intersected, then it was assumed that the floods around these turloughs merged and became one,
- if the contours in the vicinity of a turlough did not form an enclosed shape around it, then the flood was assumed to extend down gradient in an approximately oval shape,
- if the Teagasc subsoils map showed a permanent water body inside the flood, then it was not included (this approach is the same as that which was adopted in Stage 1).

The approach is illustrated in Figure 6.5a for Moran's and Ballytrasna turloughs. The +4.0 m contour gives an unrealistically large flood extent which would include more than half the area shown on the figure. The more reasonable contour of +3.0 m has been selected instead.

Sensitivity analysis was carried out using the extreme case of the 90 percentile difference instead of the median difference. The 90 percentile difference is 9.3 m. The approach is illustrated in Figure 6.5b for Gardenfield/Ardacong turlough. In this case, the flood extent defined by the 90 percentile difference would include most of the area shown in the figure. The more reasonable contour +5.0 m has been selected as representing the flood extent in the sensitivity analysis.

Many of the resultant floods using the 90 percentile difference are so extensive that there would be evidence of them in the form of reports, photographs, comments on historic maps, etc. No such evidence exists. This suggests that the use of the median difference, constrained where necessary, is reasonable. Nonetheless, two groundwater flood maps have been produced, namely: that based on the +4.0 m contour; and that based on the extreme +9.3 m contour. For both maps, the flood extents have been constrained according to the criteria listed above.



Stage 2 takes no account of the fact that groundwater flood levels are likely to vary across the country because of the nationwide variability in the amount and intensity of recharge. It is anticipated that flood levels in the east (for example those associated with turloughs in the Pure Unbedded Limestones of the Southern Valleys near Cork) will be less than those in the west. This is because there is significantly less recharge in the east compared to in the west. This issue is addressed in the second part of Stage 3.

6.2.3 Stage 3: Mapping Groundwater Flooding Based on Other Information

6.2.3.1 Part 1: Information on www.floodmaps.ie

There are 37 flood events associated with turloughs on www.floodmaps.ie for which there are easily accessible reports containing useful information such as details of the flood extent, its location and, in some cases, photographs. The turloughs are listed in Appendix F.

The reports were used where possible to corroborate or adjust the maps defined using Stages 1 and 2 of the methodology. In many cases the reports did confirm that the maps were reasonable.

A few of the events relate to flooding of the turlough system near Gort. Some were newspaper cuttings which described both the hazards (the floods) and their impact on receptors (farmland, houses, roads, etc). In all cases the reports for these events supported information that had already been obtained.

None of the reports on www.floodmaps.ie are for the 24 turloughs on the latest GSI database that are located in the eastern half of the country.

6.2.3.2 Part 2: Information from Aerial Photography and Historic Maps

A significant concern during initial mapping of groundwater flood levels was that the +4.0 m contour derived from the analysis of data in the west and north-west of Ireland is unrealistic in the east where there is significantly less recharge. Thus, use of the +4.0 m contour would over-estimate flood levels in the east.

A decision was made to examine online aerial photographs of the 24 turloughs that are located in the eastern part of the country. A source of good quality photographs at a suitable scale is http://maps.osi.ie. This online service also has some historic maps, a few of which are annotated with comments such as `line of inundation'. The flood outlines for the 24 turloughs were adjusted accordingly. Most were made significantly smaller.

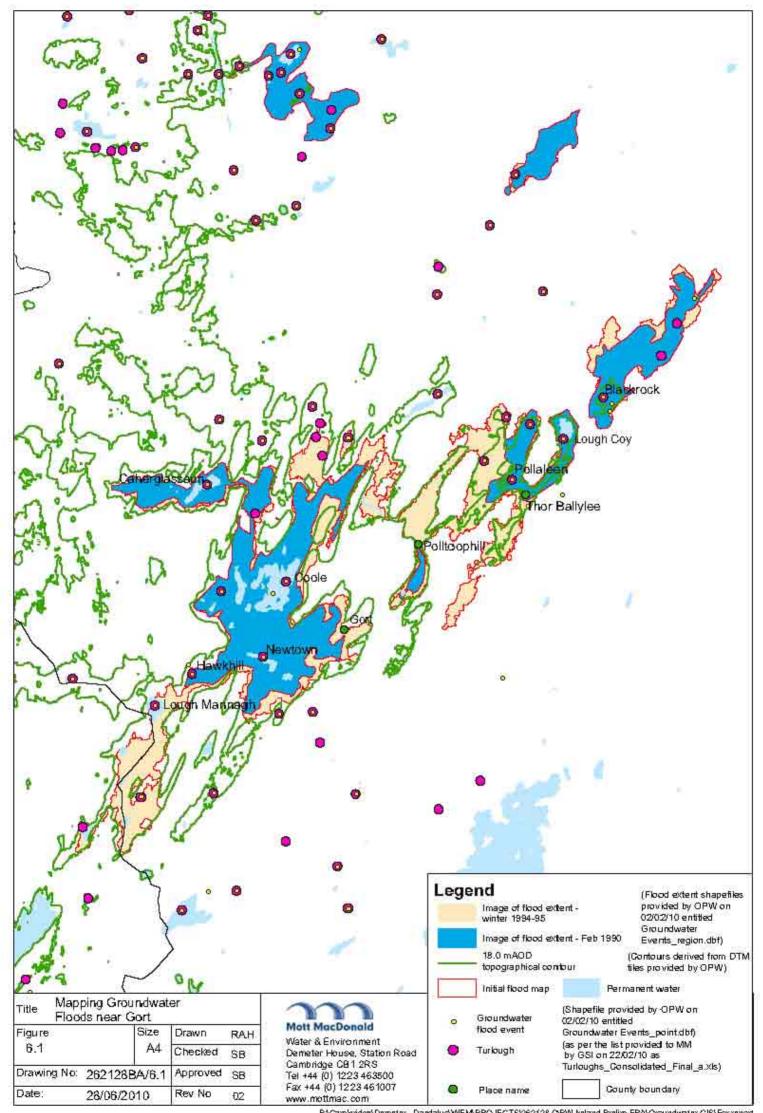
6.3 Preliminary Groundwater Flood Map

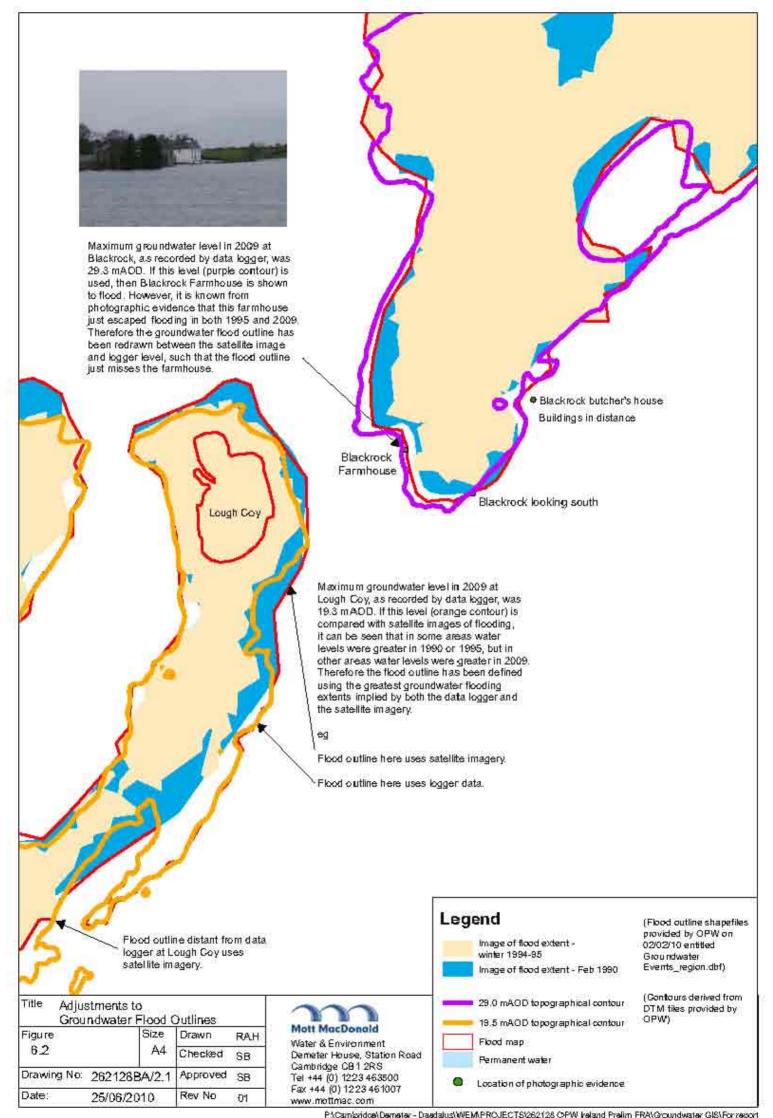
An ArcGIS shapefile delineating groundwater flooding has been produced for the whole of the Republic of Ireland. The shapefile is made up of 1879 polygons which have been drawn using one or other of the three stages of the methodology described above. The shape file is titled `Flood_ map_table_median'. The flood map (the `preliminary groundwater flood hazard map') is shown in Figure 6.6. A second shapefile (`Flood_map_table_90 percentile) delineating the sensitivity analysis based on the +9.3 m contour has also been produced. An explanation of the contents of the shapefiles is given in a spreadsheet titled `Contents of ArcGIS files'. The spreadsheet has been copied to disk.

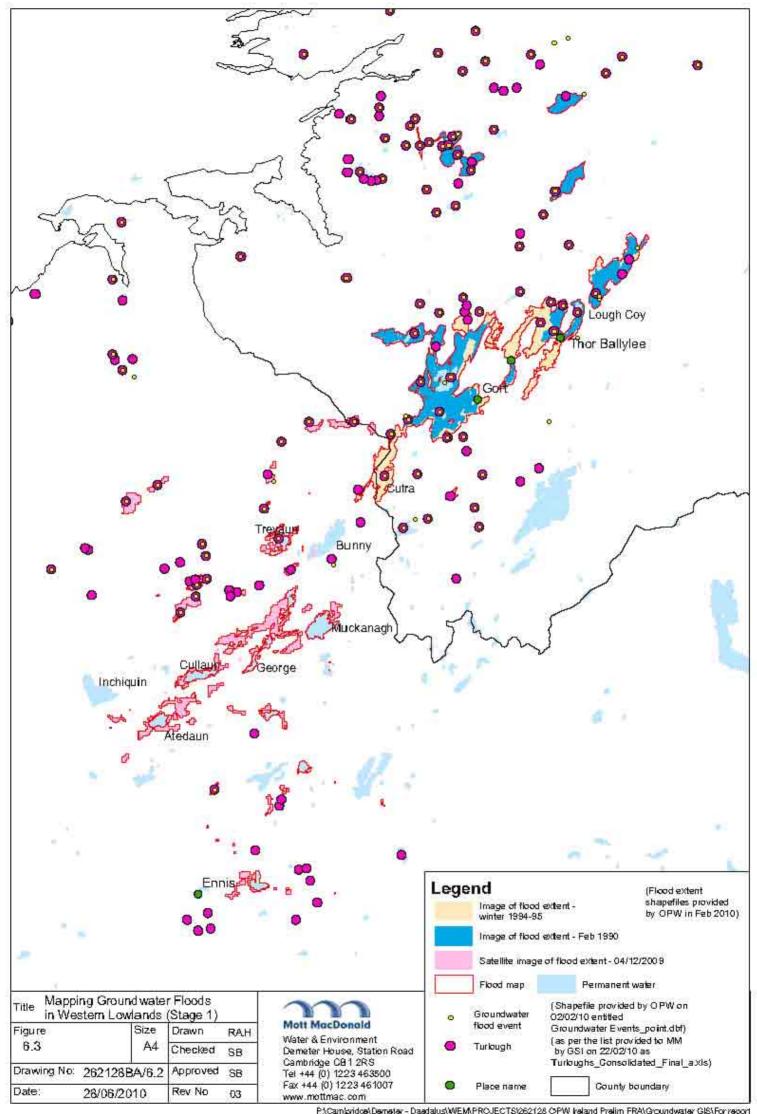
An accompanying ArcGIS project file has also been produced. The size of the file is large and consequently it has been copied to disk. It includes the following layers that can be selected or deselected as required. Some of these layers contain confidential data that are only available to OPW.

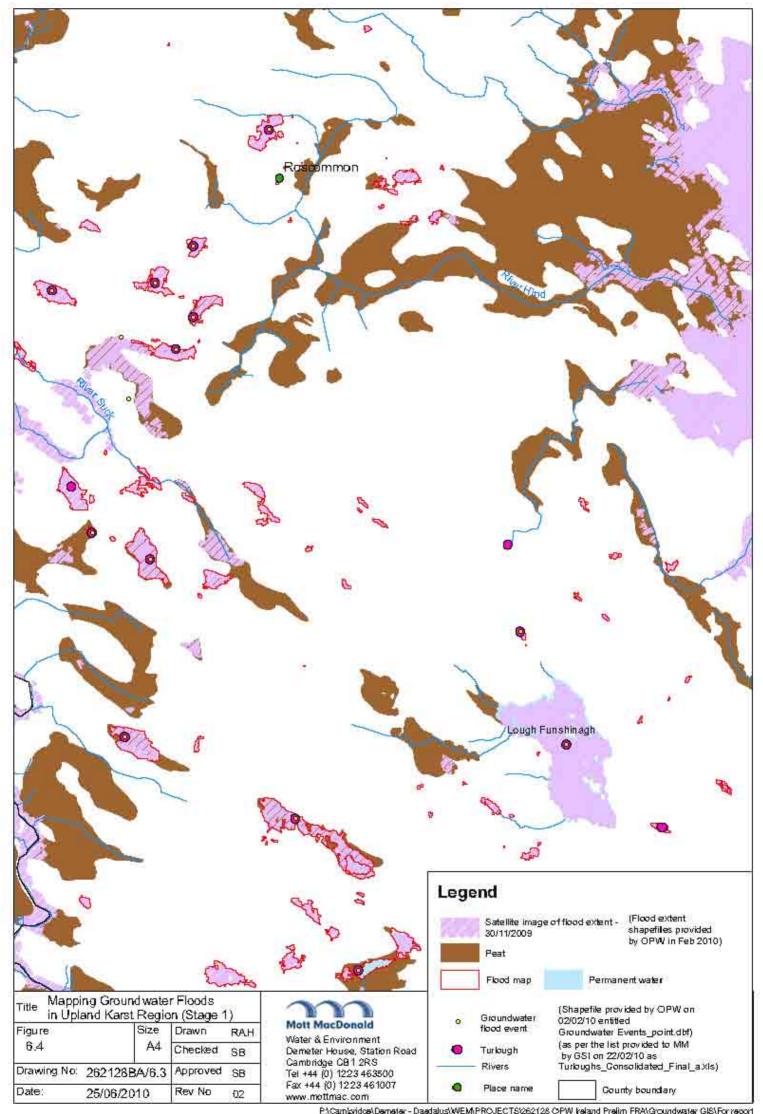


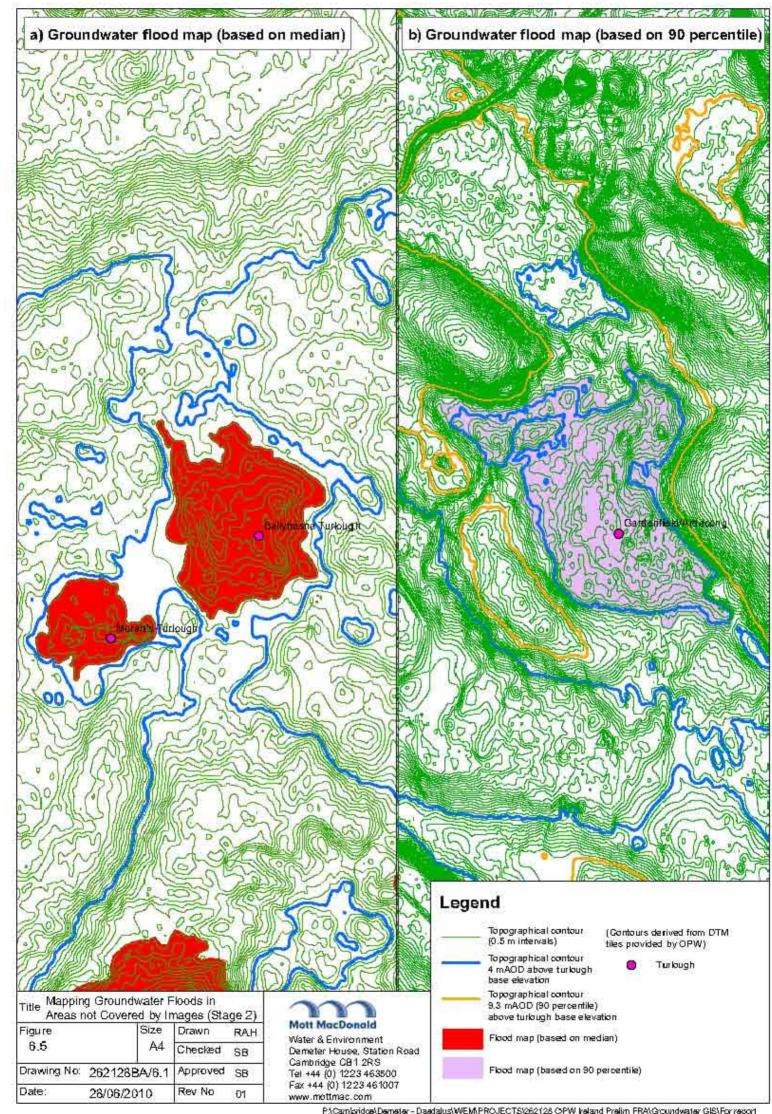
- A list of groundwater flood events for which information is available online
- Rain gauges
- Hydrometric stations
- Towns of particular interest
- Turloughs
- Springs
- Boundary lines for the area referred to in this report as the Northern Area
- Counties
- Rivers
- Groundwater flood zones that have been defined to date
- Subsoils (including permanent water features)
- Geology

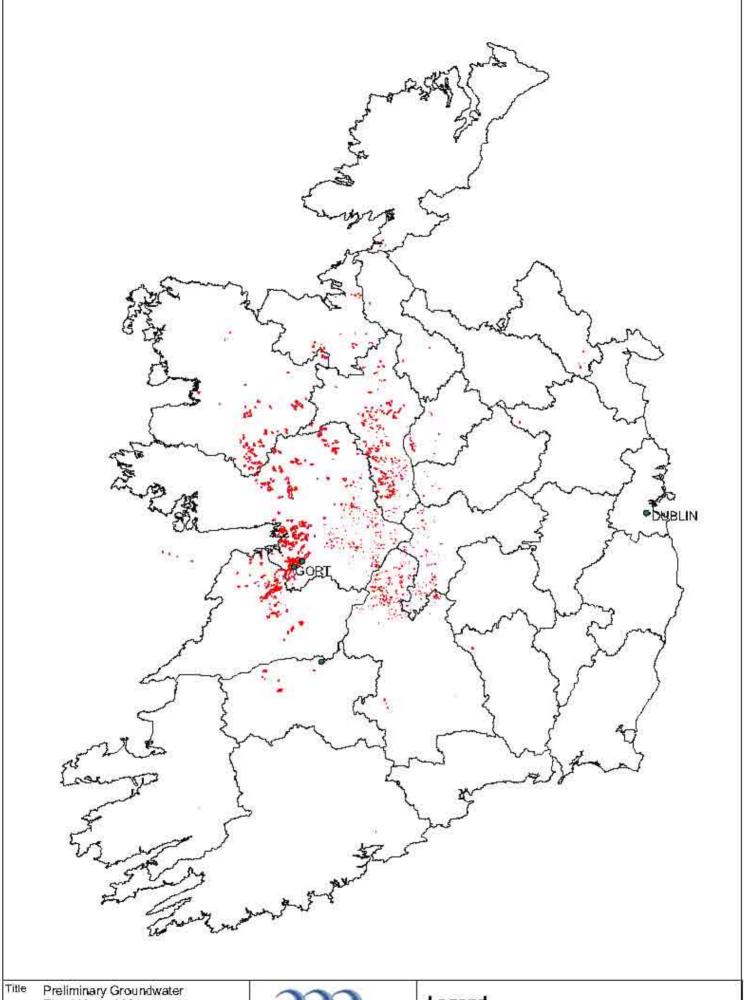












Title Preliminary Groundwater Flood Hazard Map					
Figure	3 %		Size	Drawn	RAH
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Date:		24/06/20	010	Rev No	-01

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County boundary

Location

Area at risk of groundwater flooding



Conclusions and Recommendations

7.1 Conclusions

A preliminary map of the groundwater flooding hazard in the Republic of Ireland has been produced as part of the first requirement of the Flood Directive to undertake preliminary flood risk assessments by December 2011. The map shows the outlines of groundwater floods as defined using the methodology which was developed for this project.

The assessment of the groundwater flooding hazard uses an evidence based approach incorporating the experience of groundwater experts and all available sources of information. The evidence indicates that the vast majority of extensive, recurring groundwater floods originate at turloughs. These groundwater-fed, seasonal lakes are found throughout the Republic, although they are much more common in the west and north-west than elsewhere. This is because most turloughs occur on the Pure Bedded Limestones RUG and reflect its areal distribution. The RUG is generally classified as a regionally important aquifer of karstified bedrock dominated by conduit flow.

Groundwater flooding is particularly prevalent near the town of Gort in southern County Galway. Detailed information is available concerning the nature of the karstic drainage system and the timing and extent of historic floods associated with turloughs in this area. The most severe flood in the last 50 years or so occurred in late 2009, although flood levels in 1994 – 1995 were almost as high. The information has been combined with flood images to produce maximum flood levels in the area.

Outlines of groundwater floods in other areas are less accurate because they are based on less information. However, outlines have been defined from imagery where this is available and the rest have been defined assuming that the heights of floods are 4.0 m above the base elevations of the turloughs, or can be adjusted according to a set of realistic constraints. This approach is based on the median value from statistical analysis of flood extents shown on imagery. Sensitivity analysis using the 90 percentile flood height of 9.3 m generally results in very extensive and therefore unrealistic floods.

Information in flood reports for 37 turloughs in the western half of the country has been used to adjust or corroborate the outlines. Flood reports for all other turloughs lack useful information.

The methodology has taken regional variations in recharge into account by examining aerial photographs and historic maps of the 24 turloughs on GSI's database that are located in the eastern half of the country where recharge is relatively low compared with the west and north-west. Features attributable to groundwater flooding were identified and used to check flood outlines based on the +4.0 m contour derived from data in the west and north-west. Most flood levels associated with the 24 turloughs were significantly reduced as a result of the examination.

The two principal types of maps of groundwater flooding hazards in the UK, namely Groundwater Emergence Maps and Groundwater Susceptibility Maps, have not been applied to the Irish situation because both require detailed groundwater level data. There are very few locations in the Republic where groundwater level data are collected routinely and the records of these are of short durations that mostly do not include the years when most of the severe groundwater floods have occurred. Furthermore, in karstic environments groundwater levels measured at one location may be unrepresentative of levels nearby and so are likely to be of limited value in the Irish situation.



Two other approaches to the mapping of groundwater flooding were considered but rejected. The use of areas of extreme and high vulnerability as surrogates for groundwater floods was rejected after it became apparent that the vast majority of floods are associated with turloughs. The mapping of areas encompassing springs and likely areas of shallow groundwater was rejected because there is no evidence that springs are a significant flooding hazard and the majority of their flow paths are short or very short. Also, there is virtually no data with which to accurately delineate areas of shallow groundwater.

It has not been possible to define the degree of severity represented by the preliminary hazard map of groundwater flooding. The mapped flood is based on data and information for late 2009 when the most severe flood to have affected the area of Gort in the last 50 years or so occurred. However, severe groundwater flooding in this area was less common before 1990 than in the last 20 years. This implies that a simple return period cannot be used to define flood severity.

Another issue of concern is the potential impact of climate change, but for this, all types of flooding are likely to be affected. At present it is understood that there are considerable uncertainties in climate projections at a scale applicable to the current investigation. The potential impact of climate change on groundwater flooding has been excluded from this first phase of work.

7.2 Recommendations

The methodology for development of the preliminary hazard map of groundwater flooding has been sufficiently flexible that the various issues of concern that were identified initially have been addressed and satisfactorily resolved. The map can now be used in the next phase of work without further amendments.

The next phase of work requires that groundwater flood hazard areas are incorporated into the national strategy for PFRAs.

The definition of flood risk under the PFRA study combines the mapped flood hazard areas with receptors which reflect the impact of flooding on human health, the environment, cultural heritage, and economic activity. The preliminary hazard map of groundwater flooding could be incorporated into the existing GIS along with the other mechanisms of flooding. For groundwater however there is only a single level of undefined severity. This means that groundwater flood risk will be solely dependent on the defined vulnerability of the particular receptor.

Once groundwater flood risk has been determined for each receptor, this information can be used to assist in the definition of APSRs according to the methodology that has been applied to other forms of flooding.



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Abbreviations

BGS British Geological Survey

CFRAM Catchment Based Flood Risk Assessment and Management
DEHLG Department of Heritage, Environment and Local Government

DTM Digital Terrain Model

EPA Environmental Protection Agency

EU European Union

FRMP Flood Risk Management Plan
GEM Groundwater Emergence Map

GFSM Groundwater Flood Susceptibility Map

GIS Geographic Information System
GSI Geological Survey of Ireland

GWB Groundwater Body
ING Irish National Grid

L Locally Important Aquifer

Locally Important Aquifer (Sand and Gravel)
Locally Important Aquifer (Karstified Bedrock)

Lk Poor Aquifer (Karstified Bedrock)

LI Locally Important Aquifer (Bedrock which is Moderately

Productive only in Local Zones)

Lm Locally Important Aquifer (Bedrock which is Generally

Moderately Productive)

mAOD Metres Above Ordnance Datum
mBGL Metres Below Ground Level

MM Mott MacDonald

NACP National Aquifer Classification Programme

OPW Office of Public Works
ORS Old Red Sandstone
OS Ordnance Survey

OSI Ordnance Survey of Ireland

PFRA Preliminary Flood Risk Assessment

Pl Poor Aquifer (Bedrock which is Generally Unproductive except

for Local Zones)

Pu Poor Aquifer (Bedrock which is Generally Unproductive)

R Regionally Important Aquifer

RBD River Basin District

Rf Regionally Important Aquifer (Fissured Bedrock)

Rg Regionally Important Aquifer (Extensive Sand and Gravel)

Rk Regionally Important Aquifer (Karstified Bedrock)



Rkc Regionally Important Aquifer (Karstified Bedrock Dominated by

Conduit Flow)

Rkd Regionally Important Aquifer (Karstified Bedrock Dominated by

Diffuse Flow)

RUG Rock Unit Group

SERBD South Eastern River Basin District

TCD Trinity College Dublin

UK United Kingdom

WFD Water Framework Directive

WL Water Level



Appendices

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Appendix A. Bedrock Geology and Hydrogeology

The geology and hydrogeology of the 27 bedrock unit groups defined by GSI [2009 (draft)] are described in the following sections from the oldest Precambrian rocks up to the youngest formations of Permo-Triassic age. Granites, other igneous rocks, basalts and most other volcanic rocks are of various ages and are grouped in the final sections of this appendix.

A.1. PreCambrian Rock Unit Groups

The geology and hydrogeology of the two PreCambrian groups are described in Box A.1.

Box A.1: PreCambrian Rock Unit Groups

Geology:

Precambrian rocks are the oldest in Ireland and are highly complex metamorphic **Marbles**, and **Quartzites**, **Gneisses and Schists** that have undergone at least eight phases of major folding and faulting. The two RUGs are present in County Donegal, parts of Galway and Mayo, and in a small part of County Wexford.

Hydrogeology:

The permeability of the two RUGs depends on the presence of fractures and fissures and of weathering but is generally very low. The permeability of the Marbles is likely to be somewhat enhanced by solution (some karstic features are known) where it is sufficiently thick and extensive. Most of the **PreCambrian rocks** are classed as **poor aquifers**.

A.2. Lower Palaeozoic Rock Unit Groups

The geology and hydrogeology of the three Lower Palaeozoic groups are described in Box A.2.

Box A.2: Lower Palaeozoic Rock Unit Groups

Geology:

The four Lower Palaeozoic RUGs comprise Cambrian Metasediments, Ordovician Metasediments and Volcanics, and Silurian Metasediments and Volcanics. The Cambrian rocks are present in about 1% of the country in the east, whereas the Ordovician and Silurian rocks are more widely distributed, although they occupy only about 7% and 6% respectively of the country. The Lower Palaeozoic rocks were subjected to a succession of intense episodes of folding and faulting, including the Caledonian orogeny at the end of the Silurian period that resulted in south-westerly to north-easterly trending fold axes and faults and the Variscan orogeny some 120 million years later at the end of the Carboniferous period that resulted in north-westerly to south-easterly trending faults.

In the north-east, the Ordovician and Silurian Metasediments occupy the Longford-Down Inlier where they occur as belts and fault bounded tracts. Structures are mostly upright with the rocks becoming younger to the north-west. The rocks comprise a series of sandstones, siltstones and mudstones.

In the south-east, within the SERBD, the Ordovician Metasediments and younger Ordovician Volcanics occupy the major Campile Syncline where they have been subject to multiple folding and faulting. The strata are typically steeply dipping and some beds are overturned. The metasediments are mostly soft, slatey mudstones and the volcanics are mostly pyroclastic (ash) rocks although lavas and intrusives are also present. The volcanics were deposited in two phases. The earlier rocks are 100 to 200 m thick and consist mainly of intermediate and basic rocks. The later rocks are 350 m thick and consist mainly of acidic rocks, including rhyolites (vesicular siliceous lavas, for example the Campile Formation).

Ordovician rocks occur in six fault-bounded sequences in south County Mayo. In Connemara the rocks include two small areas of meta-volcanic rocks and a regionally extensive suite of metamorphosed igneous intrusive rocks.

Silurian Metasediments are present as a south-southwesterly to north-northeasterly trending faulted belt in Counties Kildare and Wicklow. In Counties Tipperary and Limerick, they form a substantial subcrop in the Silvermine Mountains and Slieve Bloom and form the cores of the Slieve Felim, Galtee, Slievenamon and Knockmealdown mountains.



Box A.2 continued The rocks are generally similar throughout these areas, being predominantly greywackes (muddy sandstones), siltstones, mudstones and shales. In County Clare the rocks are present in the uplands of Slieve Aughty and Slieve Bernagh and are generally siltstones, mudstones and greywackes. There are other minor occurrences of similar rocks in counties Mayo, Galway and Waterford. At all locations, the rocks have been subject to south-westerly to north-easterly (Caledonian) folding and later Variscan folding and faulting.

Hydrogeology:

The permeability of the Lower Palaeozoic group of rocks depends on the presence of fractures and fissures and of weathering. However, the permeability is generally very low. **The rocks** are classed as **poor aquifers** except for a few locations where they are classed as being moderately productive only in local zones.

An exception is the **Ordovician Volcanics** that tend to be brittle, well fractured rocks with moderate to high permeability. The rhyolitic **Campile Formation** is particularly productive because it is more fissured than the other rock types in this group. Transmissivity values range between 100 and 500 m²/d. Storage values are low, being less than 0.01 where unconfined and 0.0001 where confined. Fractures are mostly oriented in a north to south direction and influence groundwater flow directions at the local scale. The **Ordovician Volcanics** are classed as a **regionally important fissured bedrock aquifer**, although there are areas where permeabilities are relatively low and where the rocks behave like a locally important aquifer.

A.3. Devonian (Old Red Sandstone and Kiltorcan- type Sandstones) Rock Unit Groups

The geology and hydrogeology of the two Devonian groups are described in Box A.3.

Box A.3: Devonian (Old Red Sandstone and Kiltorcan -type Sandstones) Rock Unit Groups

Geology:

The **Devonian Old Red Sandstone (ORS)** RUG underlies about 14% of the country and is widespread in the south, being the main rock type in Counties Kerry, Cork and Waterford where it was deposited in a deep and extensive sedimentary basin, termed the Munster Basin. The ORS also occurs in south Tipperary, north Roscommon and Mayo, and forms much of the high ground of the midlands. The rocks mainly comprise coarse and fine grained sandstones, siltstones, shales and conglomerates. They have been structurally deformed by folding and faulting during the Variscan orogeny when they were compressed from the south into a series of folds with generally east to west axes.

The **Kiltorcan-type Sandstones** are a separate RUG within the ORS. The group is present on the flanks of Slieve Bloom, Slievenamon and the Ferbane Inlier, in two adjacent areas at the base of the Galtee Mountains, and as a narrow band through Counties Waterford, Cork and Tipperary to Kilkenny, and between Newcastle West and Kilmallock in County Limerick. The group outcrops in 0.8% of the country, but dips beneath younger deposits across a significantly larger area at relatively shallow depths. The rock type generally comprises fine to medium grained, pale sandstones with minor layers of conglomerate, multi-coloured mudstones and thin limestones. It is friable in areas where calcite, dolomite and feldspar are present because these are susceptible to chemical weathering. The Kiltorcan Formation is about 235 m thick at Kiltorcan and 230 m thick at Slievenamon. It thins to the north and the west.

Hydrogeology:

The rocks of the ORS group tend to be well cemented and their permeability is therefore dependent on the presence of fractures and fissures. However, the permeability is generally low. The **ORS rocks** in the south-west and the Curlew Mountains and Slieve Aughty are **poor aquifers**. **Most of the remaining ORS group** are classed as **locally important aquifers** that are moderately productive only in local zones.

Rocks of the Kiltorcan-type Sandstones group are relatively permeable. Permeability depends on the presence of fractures and fissures except in areas where weathering has made the rock friable. Transmissivity values generally range between 40 and 100 m²/d but values of over 1500 m²/d have been obtained. Specific yields are relatively high, being about 0.02. Substantial portions of the aquifer are confined. Water levels in this aquifer vary depending on topography, ranging from near the surface to depths of over 20 m. Several large springs are used for public water supply. The **Kiltorcan-type Sandstones group** is classed as a **regionally important fractured aquifer**.



A.4. Lower Carboniferous (Dinantian) Limestones, Sandstones and Mixed Rock Unit Groups

More than half of the land area of the Republic of Ireland is underlain by rocks of Lower Carboniferous (Dinantian) age. The principal rock types are limestones, sandstones, siltstones, mudstones, shales and evaporites. There are ten RUGs as follows:

- Pure Limestones:
 - Pure Unbedded Limestones (Waulsortian)
 - Dolomitised Limestones
 - Pure bedded Limestones
- Impure Limestones
 - Lower Impure Limestones
 - Upper Impure Limestones (Calp)
- Sandstones
- Mixed (sandstone, limestone and shale)
 - Cork Group
 - Dinantian (early) sandstones, shales and limestones
 - Dinantian mixed sandstones, shales and limestones
 - Dinantian shales and limestones

The RUGs are described in Boxes A.4.1 to A.4.9 below. The sequence of boxes is in the order of the oldest to the youngest rock groups.

Box A.4.1: Dinantian Mudstones and Sandstones (Cork Rock Unit Group)

Geology:

The rocks of the **Dinantian Cork RUG** are primarily mudstones with subsidiary sandstones and limestones. They occur only in the south-west (in Counties Cork and Kerry) where they underlie an area of about 2% of the country. The rocks represent the transition from a terrestrial to marine depositional environment as the tropical seas of the Carboniferous period advanced northwards across the ORS continent.

Hydrogeology:

The permeability of the **Dinantian Cork RUG** depends on the presence of fractures and fissures and is somewhat enhanced where sandstones are present. However, the permeability is generally low. The rocks are classed as **locally important aquifers that are moderately productive only in local zones (LI).**

Box A.4.2: Dinantian Early Sandstones, Shales and Limestones Rock Unit Group

Geology:

The **Dinantian Early Sandstones, Shales and Limestones RUG** is similar to, but more varied than, the Cork RUG and occurs further north, being deposited as the tropical seas advanced northwards beyond the area of deposition of the Cork Group. The total area underlain by this group is about 1.9% of the country, the **Downpatrick Formation** in County Mayo accounting for a large proportion of the area.

Hydrogeology:

The permeability also depends on the presence of fractures and fissures and is generally low. However, it is substantially higher where sandstone and limestone beds are present. The rocks are classed as **poor aquifers** or **locally important aquifers that are moderately productive only in local zones (LI).** An exception is in the **Cavan-Monaghan area** where the rocks are classed as a **regionally important fissured aquifer (Rf)**, due to their high fissure density and juxtaposition with highly fissured RUGs.



Box A.4.3: Dinantian Lower Impure Limestones Rock Unit Group

The **Dinantian Lower Impure Limestones RUG** comprises dark grey, clayey, strongly bedded limestones that underlie about 5.4% of the country. It is informally known as ABL, or Argillaceous Bioclastic Limestone. The group is widespread and generally present around the edges of upland regions such as the Galtee Mountains and in elongate strips along the eroded limbs of north-northwesterly to south-southeasterly trending folds that are tighter in the south than further north. Most extensive faulting has occurred in the area between Cork and Waterford and in Co. Monaghan. The **Ballysteen Limestone** is the best-known rock of this group.

Karstification is very limited compared with that affecting the purer limestones. There are no high yielding springs in this group. Transmissivity values range between about 5 and 300 m²/d, although most values at the bottom end of this range. Values of effective porosity lie between 0.01 and 0.005. Groundwater movement along fractures is relatively slow and mainly within the top 30 m of the bedrock. The rocks are classed as **locally important aquifers which are moderately productive only in local zones (LI)** except for the occurrences in the Monaghan-Clones and Wexford Harbour areas, which are classed as a **regionally important fractured aquifer (Rf)**.

Box A.4.4: Dinantian Pure Unbedded Limestones Rock Unit Group

The **Dinantian Pure Unbedded Limestones RUG** comprises pure, pale grey, fine grained, massive, fossiliferous limestones that are present across a substantial area of Ireland, but mainly in the midlands, in the southern synclinal valleys and in the border counties of Cavan and Monaghan. The limestones were deposited as large unbedded carbonate mounds on the floor of a tropical sea that coalesced with time to form continuous masses. Estimates of original depositional thicknesses range from up to 1200 m in north-west County Limerick, to less than 100 m near Gort in Co. Galway.

The limestones were folded and faulted during the Variscan orogeny and are mostly present in synclinal folds that have a general east to west orientation, particularly in the south where the synclines coincide with present day valleys separated by intervening, older sandstone ridges. The relative competence of the RUG means that it has been more resistant to folding and fracturing than the bedded limestones. major north to south normal faults cut across the folds and are paralleled by a very well developed system of vertical joints in the south. There is less fracturing in the north.

The limestones are susceptible to karstification and evidence of this is widespread in the south though less so in the north. There is a general absence of surface drainage in the valleys of Counties Cork and Waterford and sinking streams, springs and extensive cave systems are common. Transmissivity values range between about 30 and 13000 m²/d. Groundwater flow in the south occurs through three separate depth zones that are variably karstified and fractured. Flow in the north predominantly occurs in the upper more weathered zones. The **Pure Unbedded Limestones RUG** is classed as a **locally important aquifer (LI)** in the midlands and as a **regionally important karstified aquifer (Rk)** elsewhere.

Box A.4.5: Dinantian Dolomitised Limestones Rock Unit Group

The **Dinantian Dolomitised Limestones RUG** comprises limestones in which more than 90% of the original calcite has been replaced by dolomite. The RUG is present in 0.4% of the country and mainly occurs as narrow arcuate bands between Callan and Carlow, and south of Wexford. Over most of their extent, the rocks have been folded into a north-easterly to south-westerly trending broad syncline and associated smaller folds and have been extensively faulted and severely jointed.

Some karstic features occur in this group and there are two large springs at Thurles (North Tipperary) and Woolengrange (County Kilkenny). However, groundwater more commonly discharges into local surface waters via small springs or as baseflow. The process of dolomitisation has increased the porosity and permeability of the rock and in some places weathering has reduced the rock to the texture of sand. Transmissivity values are between 250 and 400 m²/d. Groundwater levels are generally less than 10 m below the surface and flows are at shallow depths and relatively rapid. GSI [Section 16.2.8, 2009 (draft)] gives details of the relationships between the aquifer, overlying subsoils, and surface waters. The **RUG** is classed as a **regionally important karstified aquifer dominated by diffuse flow (Rkd)**.

Box A.4.6: Dinantian Upper Impure Limestones and Dinantian Pure Bedded Limestone Rock Unit Groups

The Dinantian **Upper Impure Limestones** and **Pure Bedded Limestones RUGs** both generally comprise well-bedded, fine to coarse grained limestones with varying amounts of chert and shale bands. The difference between the two is that the former is coloured dark grey by the presence of shales and mudstones and the latter is pale grey without these impurities. The RUGS were laid down after the Pure Unbedded Limestones RUG and are contemporaneous with each **Box A.4.6 continued** other, representing sediments in shallow tropical seas (pure limestones) and deep basins (impure



limestones).

The **Upper Impure Limestones RUG** (often called 'Calp') is widespread but the **Pure Bedded Limestones RUG** has a significantly greater areal extent amounting to about 16.7% of the country. In the south and south-east the RUGs are generally found together as dipping beds around the edges of upland regions such as the Galtee Mountains and Slieveardagh Hills. They are also found as tightly folded, heavily faulted beds and as broad arcuate bands in the cores of synclines. In geographical contrast, the **Upper Impure Limestones RUG** is mainly flat lying and extensive in the midlands from the east of County Galway across to County Dublin. In Counties Mayo, Sligo and Leitrim the RUG is less flat lying and occurs in thinner, more complex bands. Also in geographical contrast to the south and south-east, the **Pure Bedded Limestones RUG** is flat lying and very extensive in the west from Counties Clare to Mayo and across to Co. Roscommon and Leitrim, and in the north-west in Co. Sligo and Leitrim.

Although the **Upper Impure Limestones RUG** is not generally karstified, some karstic features do exist. Numerous small seeps and springs issue from this unit, often at its boundary with the more permeable pure limestones. In low-lying areas the water table is often less than 2 m below the ground surface. Elsewhere, it is relatively shallow and closely mirrors the topography. Transmissivities range between 2 and 300 m²/d, with most values at the lower end of the range. Over most of Ireland the **Upper Impure Limestones RUG** is classed as a **locally important aquifer which is moderately productive only in local zones (LI)**. However, south of the Galtee Mountains it is classed as a **regionally important karstified aquifer dominated by diffuse flow (Rkd)**.

The **Pure Bedded Limestones RUG** is notable for the presence of karstic features of all kinds, particularly in the Burren, the Gort-Kinvara area, in County Roscommon, and the North-west Plateau in Counties Sligo and Leitrim. Karstification is also well developed in the south and midlands but to a lesser degree than in the west. Most springs are relatively small although much larger springs are characteristic of this group (at least 200 springs have discharges of more than 100 l/s, the springs at Kinvara and Cong having the greatest discharges of between 5000 and 30000 l/s). The interaction between surface water and groundwater is critical in terms of groundwater flooding, particularly in the western lowlands of Counties Clare, Galway and Mayo. Where karstic features are well developed, groundwater flow can be very rapid and at several depths with flow directions controlled by a combination of these features and the regional (not local) hydraulic gradient. As with most karstic systems, transmissivity data are very variable. The available data range between about 20 and 3000 m²/d. Two values of effective porosity, calculated from tests in County Offaly, are both 0.0002. This very small value indicates that the aquifer storage is very low. The RUG is classed as a **regionally important karstified aquifer (Rk)** throughout Ireland and as one that is **dominated by conduit flow (Rkc)** in all areas except the south and east.

Box A.4.7: Dinantian Sandstones Rock Unit Group

The **Dinantian Sandstones RUG** consists of variable sandstones that were deposited in deltaic conditions at various times during the Lower Carboniferous period but which are similar to each other. The RUG is present in the north-west and underlies about 1.5% of the country. Structural features include several major synclines. Major faults with north-east to south-west and east to west trends occur in the Counties Sligo to Leitrim area.

The permeability of the **Dinantian Sandstones RUG** depends on the presence of fractures and fissures. There are few available aquifer property data. However, the rocks are classed **as locally important aquifers that are moderately productive to moderately productive only in local zones (Lm to LI).**

Box A.4.8: Dinantian Mixed Sandstones, Shales and Limestones Rock Unit Group

The **Dinantian Mixed Sandstones, Shales and Limestones RUG** comprises interbedded sandstones, shales and limestones that were deposited at different times within the Carboniferous period but which are grouped together because of their similarities. This group occurs primarily in north-west Ireland and occupies about 0.9% of the country. Due to the thickness of overlying subsoils, many of the formations in this group are rarely seen at the surface and their structures have therefore not been mapped in detail.

Permeability is generally low but significantly higher in some areas. Well yields and productivities are generally low, and the few available transmissivity values range between 14 and 100 m^2/d . The rock unit is generally classed as a **locally important aquifer that is moderately productive only in local zones (LI)**, although **generally moderately productive (Lm) aquifers** also occur within this RUG.

Box A.4.9: Dinantian Shales and Limestones Rock Unit Group

The Dinantian Shales and Limestones RUG consists of shales and limestones that were deposited at different times



within the Carboniferous period but which are grouped together because of their lithological similarities. This group occurs primarily in the north of Ireland and occupies about 1.4% of the country. The rocks are gently folded, and in the Monaghan-Clones area are cross-cut by numerous north-south faults.

Dissolution and dolomitisation of limestone interbeds occurs. However, karst features are not well developed and there are no recorded high yielding springs. Almost no data are available on aquifer properties. The rock unit belongs variously within the **locally important** and **poor aquifer** classes.

A.5. Upper Carboniferous (Namurian) Rock Unit Groups

The two Upper Carboniferous (Namurian) RUGs are described in Box A.5.

Box A.5: Namurian Shales and Namurian Sandstones Rock Unit Groups

Geology:

The two RUGS of Namurian age rocks generally comprise fossiliferous shales, siltstones and sandstones. The siltstones and sandstones are often thickly bedded (examples include the Carrickleck Formation and the Carrickleck Sandstone Member at Kingscourt in the north-east) and are younger than the shales. The rocks formed on continental slope and in deep offshore basins towards the end of the Carboniferous period about 325 million years ago. They replaced the older limestone rocks which ceased to be deposited because of climate change. The rocks mostly occupy the south-west and south midlands of Ireland, with two main areas of occurrence in Counties Clare, Limerick and Kerry, and the Castlecomer Plateau and Slieveardagh Hills. Smaller areas of Namurian rocks occur at Kingscourt, north of Dublin, and on the uplands around Lough Allen in the north-west. Namurian age rocks occur in 8% of the country.

The rocks were uplifted, folded and faulted during the Variscan orogeny at the end of the Carboniferous period. The rocks are typically folded into north-easterly to south-westerly trending synclines or basins, such as those which underlie the Castlecomer Plateau. The effects of the orogeny were more severe in the south-west than further north.

Hydrogeology:

Karstification and dolomitisation do not occur in the Namurian RUGS, but the unconformity between the rocks and the underlying pure bedded limestone is often marked by karstic features due to relatively acidic runoff from the RUGS. There are no high yielding springs. The depth to the water table is often very shallow. Permeability depends on the presence of fractures and fissures. Aquifer characteristics are mostly poor, and even in the more permeable sandstones, such as the Carrickleck Formation, transmissivity values are less than about 100 m²/d. The two RUGs are classed as **poor or locally important aquifers (Pu, PI or LI)**, except for the **Carrickleck Formation** which is classed as **a locally important aquifer that is generally moderately productive (Lm)**.

A.6. Upper Carboniferous (Westphalian) Rock Unit Groups

The two Upper Carboniferous (Westphalian) RUGs are described in Box A.6.

Box A.6: Westphalian Sandstones and Shales Rock Unit Groups

The two RUGS of Westphalian rocks comprise variable coal bearing **Sandstones** and **Shales**. They are principally found in association with the older Namurian rocks in the Castlecomer Plateau and Slieveardagh Hills, but are present at some other locations. They occur in about 0.5% of the country, the Sandstones RUG amounting to about 30% of this area. The Shales RUG comprises mainly shales or mudstones with minor coal seams and fireclays.

Permeability depends on fractures and fissures which are more prevalent in the Sandstones RUG that the Shales RUG. Transmissivity values in the Sandstones RUG range from 1 to almost 500 m²/d, the higher values being associated with major faults. The **Sandstones RUG** is classed as **locally important generally moderately productive aquifers (Lm)**. The **Shales RUG** comprises **poor aquifers**, **which are generally unproductive (Pu)**.

A.7. Permo-Triassic Rock Unit Groups

The two Permo-Triassic RUGs are described in Box A.7.



Box A.7: Permo-Triassic Mudstones and Gypsum and Sandstones Rock Unit Groups

Permo-Triassic rocks in the Republic of Ireland are found in only about 0.05% of the country in the area of Kingscourt in the north-east where, along with Carboniferous rocks, they occupy a small fault bounded inlier surrounded by Lower Palaeozoic rocks. There are two RUGs: **Mudstones and Gypsum**; and **Sandstones**. The latter has the potential for relatively high fissure permeability and transmissivity values in the range from 10 to about 150 m²/d are expected, particularly in the vicinity of faults. The **Sandstones RUG** is classed as **locally important and generally moderately productive aquifers (LI and Lm)**. In contrast, the **Mudstones and Gypsum RUG** is classed as **poor (PI)**.

A.8. Granites and Other Intrusives Rock Unit Group

Granites and other intrusive rocks were emplaced in two main phases of activity: during the Caledonian orogeny between 410 and 350 million years ago; and during the Tertiary era about 60 million years ago. The geology and hydrogeology of this group of rocks is described in Box A.8.

Box A.8: Granites and Other Intrusives Rock Unit Group

Four areas of the Republic of Ireland have major granite intrusions: the Leinster Granite (1500 km² from Dun Laoghaire to New Ross and the largest granite body in Britain and Ireland); the Donegal Granite (949 km²); the Galway or Connemara Granite (701 km²); and the Newry and Carlingford Granites (213 km²). The total area amounts to 5.2% of the country. Other rock types in this group are mainly fine grained igneous dykes and sills associated with the emplacement of the granites. All the granites apart from the Carlingford Granite date from the first phase of activity.

Fresh granite has very low porosity and permeability but zones of enhanced permeability occur near faults, along joints and in the weathered zone above the fresh rock. The **granites** are generally classed as **poor (PI)**, **or locally important (LI) aquifers**.

A.9. Basalts and Other Volcanics Rock Unit Group

Basalts and other volcanic rocks are described in Box A.9.

Box A.8: Basalts and Other Volcanics Rock Unit Group

The group of basalts and other volcanic rocks are Carboniferous in age and formed as lava flows and layers of silica rich, vesicular tuff. The rocks occur in widely scattered small areas that in total occupy less than 0.2% of the country. Permeabilities are related to the presence of vesicles and weathered horizons and, in the basalts, by the presence of columnar jointing. Very little hydrogeological information is available for this group of rocks. They are primarily classed as locally important aquifers, productive only in local zones (LI), although locally important generally moderately productive (Lm) basalt aquifers are found at Edenderry, County Offaly.



Appendix B. Sand and Gravel Geology and Hydrogeology

There are five extensive sand and gravel deposits in the Republic of Ireland, all of which are located in the SERBD. These are all classed as regionally important aquifers (Rg). Less extensive deposits are of local importance (Lg). The information is derived from Chapter 26 and its appendix of GSI [2009 (draft)], Tedd el al [2010], and summary reports of characterisations of groundwater bodies downloaded from the webpage www.gsi.ie. The regionally important aquifers are described in Boxes B.1 to B.5. The most significant of the locally important aquifers are listed Box B.6.

Box B.1: Mid Kildare Sand and Gravel

The glacio-fluvial **Mid Kildare Sand and Gravel** aquifer occupies a north-easterly to south-westerly orientated shallow limestone trough and covers an area of about 200 km². The dominant lithology is sandy gravel or gravelly sand with occasional clay horizons, but extensive lateral variability occurs. The deposit is between 20 and 60 m thick, with an estimated maximum thickness of 110 m. It is classed as a regionally important aquifer and behaves in an unconfined manner in most places although it is locally capped by till. Borehole yields are high and estimated permeability values range between 10 to 100 m/d. Porosity values are very high, being in the order of 30 to 40%. The aquifer is an important source of baseflow for surface waters and depths to the water table are shallow adjacent to surface waters to which the aquifer provides significant quantities of baseflow. Hydraulic gradients are very shallow and seasonal variations are small, reflecting the high specific yield of this aquifer.

Box B.2: Barrow Valley Sand and Gravel

The fluvial Barrow Valley Sand and Gravel aquifer occupies the valley of the River Barrow from Athy to a few kilometres south of Bagenalstown and covers an area of about 127 km². The deposit consists of interbedded very coarse and poorly sorted sands and gravels and sands and clays. Tills are common above individual sand and gravel units. The deposit thickens from west to east and is between 10 and 25 m thick. Estimated permeability values are in the order of 30 to 40 m/d, porosities are high, and specific yields between 5 and 10% are likely. Most groundwater levels are less than 2 m below ground and groundwater discharges occur as baseflow to the River Barrow.

Box B.3: Nore River Sand and Gravel

The glacio-fluvial Nore River Sand and Gravel aquifer occurs in the River Nore valley from north of Abbeyleix to south of Kilkenny and has an areal extent of 80 km². Lithologies are similar to those of the Barrow Valley Sands and Gravels. The deposit is up to 30 m thick. The aquifer properties of this deposit are not well documented. The aquifer contributes baseflow to the River Nore. Groundwater levels lie between 2 and 20 m below ground.

Box B.4: Kilmanagh River Sand and Gravel

The Kilmanagh River Sand and Gravel aquifer occupies an area of about 30 km² in the valley of the Kilmanagh River on the south-east side of the Slieveardagh Hills between Tullaroan and Calllan. The deposit is believed to be outwash material and consists of coarse grained sand and gravel with a variable but low silt and clay content. Thicknesses range up to about 15 m. An example of the geological characteristics of this deposit is given in the log of a borehole at Oldtown (at NGR 238700 154400, see Tedd et al [2010]). This shows 15 m of sand and gravel with a clay band from 5 to 6 m below ground, on 3 m of till, on bedrock of Namurian sandstones and shales. The aquifer is unconfined between Tullaroan and Kilmanagh but confined by till elsewhere. Transmissivity values are between 200 and 250 m²/d and porosities are in the order of 10 to 25%. Most groundwater discharge from the aquifer is believed to occur to the Kilmanagh River. Seasonal variations in groundwater levels are relatively small and levels are generally shallow. Analysis of the hydrograph of water levels at the Oldtown borehole gives a range between 0.81 and 3.43 m below ground and a mean of 2.02 m.

Box B.5: Roscrea Gravel

The Roscrea Gravel occupies an area of 46 km² in north Tipperary and Offaly. Little is know about the deposit except that it is high yielding, may have less than 4% of fines, and is at least 60 m deep in places. It has been exploited for industrial uses in and around Roscrea.



Box B.6: Other Sand and Gravel of Potentially Local Significance

Other sand and gravel deposits of potentially local significance are briefly described in GSI [2009 – draft]. These include:

- Sand and Gravel with an areal extent of about 100 km² north of Wexford (there is little published information on this relatively extensive deposit and the summary of the relevant groundwater body (Kilmuckridge) is not available on the GSI webpage0
- Carndonagh Gravel between Carndonagh and Trawbreaga Bay in County Donegal
- Gravel Deposit between Killarney and Killorglin in County Kerry
- Blessington Sand and Gravel in County Wicklow
- Cooley Peninsula Gravel in County Louth
- Tallaght buried valley deposit in south-western suburbs of Dublin city
- Carrigtwohill buried valley deposit east of Cork city
- Gleneely River Deposit in County Donegal
- Carrigans Alluvial Deposit in County Donegal
- Duagh Alluvial Deposit in County Kerry
- Brinny /Upton Gravel in County Cork
- Minane Bridge Sand and Gravel in County Cork
- Bandon River Sand and Gravel between Dunmanway and Enniskean in County Cork
- Lee Valley Sand and Gravel west of and beneath Cork city
- Fanad Head Blown Sand in County Donegal
- Ballyshannon Blown Sand in County Donegal
- Rossnowlagh Raised beach Sand in County Donegal
- Ardfert Sand in `pocket' on karst limestone in County Kerry



Appendix C. Description of GSI Aquifer Classifications

Regionally Important Aquifers: Bedrock aquifer unit capable of supplying regionally important abstractions (e.g. large public water supplies), or 'excellent' yields (>400 m³/d). The continuous aquifer unit generally has an area of >25 km². Groundwater flow predominantly occurs through fractures, fissures and joints. Sands and Gravels generally >10km² with proven yields.

Rk Regionally Important Karstified Bedrock Aquifer: 'Karstification' is the process whereby limestone is slowly dissolved away by percolating waters. It most often occurs in the upper bedrock layers and along certain fractures, fissures and joints, at the expense of others. Karstification frequently results in the uneven distribution of permeability through the rock, and the development of distinctive karst landforms at the surface (e.g. swallow holes, caves, dry valleys), some of which provide direct access for recharge/surface water to enter the aquifer. The landscape is characterised by largely underground drainage, with most flow occurring through the solutionally-enlarged, interconnected fissure/conduit zones, which may be several kilometres long. Groundwater velocities through fissures/conduits may be high and aquifer storage is frequently low. Groundwater often discharges as large springs (>2000 m³/d), which range from regular and dependable to highly variable ('flashy'). There is strong interconnection between surface water and groundwater. The degree of karstification ranges from slight to intense. GSI recognises two types of karst aquifers: those dominated by **diffuse flow (Rkd)** and those dominated by **conduit flow (Rkc)**.

Rf Regionally Important Fissured Bedrock Aquifer: Aquifer in which the network of fractures, fissures and joints, through which groundwater flows, is well connected and widely dispersed, resulting in a relatively even distribution of highly permeable zones. There is relatively good aquifer storage, and groundwater flow paths can be up to several kilometres in length. Substantial groundwater discharge to surface waters likely ('baseflow') and large (>2000 m³/d), dependable springs may be associated with these aquifers.

Rg Regionally Important Sand and Gravel Aquifer: A sand and gravel aquifer is classed as regionally important if it can sustain regionally important abstractions (e.g. large public water supplies), or many 'excellent' yields (>400 m³/d). It is highly permeable, more than 10 m thick or has a saturated thickness of at least 5 m, and normally extends over at least 10 km². Groundwater flows through the pore spaces between sand/gravel grains, and permeability is mainly determined by the grain size (larger grains give larger pore spaces), and the 'sorting' of the material (more uniform grain sizes give higher permeability). There is a relatively uniform distribution of groundwater, good aquifer storage and long groundwater flow paths, typically limited by the aquifer's extent. Groundwater gradients are typically low ('flat' water tables), giving relatively low groundwater velocities. There is generally a strong interaction between surface water and groundwater, with groundwater discharging into streams if the water table is high, or conversely, the surface water moving into the aquifer, if the surface water level is high. Large, dependable springs (>2000 m³/d) are often associated with these aquifers, especially in low-lying areas or at the periphery of the aquifer.



<u>Locally Important Aquifers</u>: Bedrock aquifer unit capable of supplying locally important abstractions (e.g. smaller public water supplies, group schemes), or 'good' yields (100-400 m³/d). Groundwater flow occurs predominantly through fractures, fissures and joints.

Lm Locally Important Bedrock Aquifer, Generally Moderately Productive: Aquifer in which the network of fractures, fissures and joints through which groundwater flows is reasonably well connected and dispersed throughout the rock, giving a moderate permeability and groundwater throughput. Aquifer storage is moderate and groundwater flow paths can be up to several kilometres in length. There is likely to be a substantial groundwater contribution to surface waters ('baseflow') and large (>2000 m³/d) dependable springs may be associated with these aquifers. This classification also includes aquifers similar to the Regionally Important Fractured Bedrock Aquifer (Rf), but with a smaller continuous area (<c.25 km²). Although the aquifer may supply 'excellent' yields, the small size limits the amount of recharge available to meet abstractions.

LI Locally Important Bedrock Aquifer, Moderately Productive only in Local Zones: Aquifer with a limited and relatively poorly connected network of fractures, fissures and joints, giving a low fissure permeability which tends to decrease further with depth. A shallow zone of higher permeability may exist within the top few metres of more fractured/weathered rock, and higher permeability may also occur along fault zones. These zones may be able to provide larger 'locally important' supplies of water. In general, the lack of connection between the limited fissures results in relatively poor aquifer storage and flow paths that may only extend a few hundred metres. Due to the low permeability and poor storage capacity, the aquifer has a low 'recharge acceptance'. Some recharge in the upper, more fractured/weathered zone is likely to flow along the relatively short flow paths and rapidly discharge to streams, small springs and seeps. Groundwater discharge to streams ('baseflow') can significantly decrease in the drier summer months.

Lk Locally Important Karstified Bedrock Aquifer: Essentially similar to the Regionally Important Karstified Bedrock Aquifer (Rk), but with a smaller continuous area (<c.25 km²). Although the properties imply that this aquifer can supply 'excellent' yields, the smaller size limits the amount of recharge available to meet abstractions.

Lg Locally Important Sand/Gravel Aquifer: Similar to a Regionally Important Sand/Gravel Aquifer (Rg), but with a smaller continuous area (c.1-10 km²) and/or less consistent permeability. Although the aquifer may supply 'excellent' yields, the smaller size limits the amount of recharge available to meet abstractions.

<u>Poor Aquifers</u>: Bedrock aquifer capable of supplying small abstractions (e.g. domestic supplies, small group schemes), or 'moderate' to 'low' yields (<100 m³/d). Groundwater flow occurs predominantly through a limited and poorly-connected network of fractures, fissures and joints.

PI Poor Bedrock Aquifer, Moderately Productive only in Local Zones: Similar to a Locally Important Bedrock Aquifer, Moderately Productive only in Local Zones (LI), but with fewer and more poorly-connected fractures, fissures and joints, and with less permeable and/or more limited zones of higher permeability. Overall permeability, storage capacity, recharge acceptance, length of flow path and baseflow are likely to be less than in LI aquifers.

Pu Poor Bedrock Aquifer, Generally Unproductive: Aquifer with generally few and poorly connected fractures, fissures and joints. This low fissure permeability tends to decrease further with depth. A shallow zone of slightly higher permeability may exist within the top few metres of more fractured/weathered rock, and higher permeability may rarely occur along large fault zones. In general, the poor fissure network results in poor aquifer storage, short flow paths (tens of metres) and low 'recharge acceptance'. Groundwater discharge to streams ('baseflow') is very limited.



Appendix D. Aquifers and Groundwater Flooding

Regionally Important Karstified Aquifers Rk, Rk^c and Rk^d:

General Hydrogeological Description:

Karstification is a process that principally affects limestones. It is enhanced in 'pure' limestones, in limestones with higher frequencies of discontinuities (fractures, joints and bedding planes), and in places where the circulating groundwater is more chemically aggressive to carbonate. Karstified RUGs include **Pure Bedded Limestones**, **Pure Unbedded Limestones** and **Dolomitised Limestones** (all Dinantian), the first being the most areally extensive. Karstification results an uneven distribution of permeability with certain fissures enlarged at the expense of others, and the concentration of groundwater flow into these high permeability zones. It also results in the progressive development of distinctive karst landforms such as collapses, caves, swallow holes, dolines, sinking streams, turloughs and dry valleys, and a distinctive groundwater flow regime where drainage is largely underground in solutionally-enlarged fissures and conduits. GSI recognises two karst aquifer types: karstified aquifers dominated by conduit flow (\mathbf{Rk}^c) and karstified aquifers dominated by diffuse flow (\mathbf{Rk}^d).

There are five karstic regions in the Republic of Ireland [Ball et al 2000]: the **North-West Plateau Karst**, the **Burren**, the **western lowlands**, the **east midlands**, and the **southern valleys**. These belong to two main types of landscape: **upland karst** (such as the Burren and along the Cavan-Fermanagh border), and **lowland karst** (principally in the western lowlands region of the Fergus River valley in Co. Clare, the Gort area in Co. Galway, and Loughs Mask and Corrib in Co. Galway and southern Co. Mayo). Upland karst areas have altitudes between about 100 and > 300 mAOD, incised valleys and steep-sided hills. Lowland karst areas are typically flat-lying or gently undulating, and range in altitude from sea level to about 150 mAOD. Upland karst areas have a thin, sparse or no cover of subsoils, whereas subsoils may be more than 40 m thick in lowland karst areas [Drew, 2008]. Both landscapes are formed predominantly on **Pure Bedded Limestones** [Drew 2008, Tynan et al 2006]. This limestone belongs to the aquifer category Rk^c.

Groundwater flow paths are typically kilometres long. Transmissivity ranges from a few m²/d up to a few thousand m²/d. There are no published storage values although effective porosity values of 0.02 from two tests in Co. Offaly indicate that aquifer storage can be very low, as is the generally held perception by hydrogeological experts. Groundwater flow velocities in conduit systems range between 70 and 3500 m/d (120 to 6000 m/d in lowland karst [Drew, 2008]) but are lower within more diffusely karstified systems. Hydraulic gradients in lowland karst areas range from 0.001 to 0.01 and are typically an order of magnitude higher in upland karst areas [Drew 2008]. A conventional piezometric surface is identifiable in the folded Pure Unbedded Limestone of the Southern Valleys, but may be absent in the flatter bedded Pure Bedded Limestones in the west and north-west [Drew 2008, Southern Water Global 1997, Drew and Daly 1993].

Groundwater and Surface Water Interaction:

There is a high degree of interconnection between groundwater and surface water. Diffusely karstified systems frequently support large (>2000 m³/d) dependable springs. Karst systems dominated by conduit flow also have large springs (those at Kinvara and Cong have huge discharges of between 430 x 10³ and 2580 x 10³ m³/d) but these tend to be flashy and may reduce to a trickle in dry weather. Surface streams often sink, draining into the groundwater system, providing rapid recharge to groundwater. They may re-emerge as springs, after flowing as groundwater for some distance. Turloughs (seasonal lakes which are fed by groundwater as the water table rises in winter) are common although most are located in the western lowlands. Of the 482 turloughs on GSI's most recent database, 438 are located on Pure Bedded Limestones and 10 on Pure Unbedded Limestones. Baseflows can be very variable with peaky surface water hydrographs and a rapid response to rainfall. This is due to very low aquifer storage and high groundwater velocities, particularly for Rk^c aquifers. Karstic landscapes tend to be characterised by low drainage densities because water is readily accepted into the subsurface.

Groundwater Flooding:

Extensive groundwater flooding is not common in upland karst, but can be regionally extensive in lowland karst. Floods occur as the piezometric surface rises rapidly above ground level in response to exceptionally high rainfall. Almost all the floods occur at turloughs. Those in the Gort area in Co. Galway are the most areally extensive and have the greatest impact [Daly 1985, 1992 and 1993, Mac Dermot 1991 and 1995, Drew and Daly 1993, Southern Water Global 1997, Tynan et al 2006, Drew 2008, and unpublished work by Johnston of TCD].



Regionally and Locally Important Fissured Bedrock Aguifers Rf and Lm:

General Hydrogeological Description:

In regionally and locally important fissured bedrock aquifers, groundwater flows through the subsurface via a network of discontinuities in the rock such as joints, faults, fractures and bedding planes. Fractures and faults originate during the deformation of the rock mass caused by large-scale compression (folding and mountain-building) or extension (rift valley development). Fracturing can also result from non-structural effects; e.g. the cooling of igneous rocks and stress relief after deep burial. The fissures form a well-connected network within the rock mass. Rock types mostly comprise thin-bedded sandstones (sometimes only weakly cemented), some volcanic rocks, and thin-bedded, cherty limestones. There may be limited karstification within the limestones. The Ordovician Volcanics in Counties Waterford, Kilkenny and Wexford is the most extensive Rf aquifer. It comprises well fractured rocks with moderate to high permeability. The rhyolitic Campile Formation is particularly productive because it is more fissured than the other volcanics. Transmissivities range between 100 and 500 m²/d and specific yields are quite low, being less than 1%. Fractures are mostly oriented in a north to south direction and influence groundwater flow directions at the local scale. The Kiltorcantype Sandstones is classed as an Rf aguifer. It mainly occurs in the south-east on the flanks of the Slieve and Galtee Mountains and the Slievenamon Hills and as narrow bands elsewhere. Transmissivities generally range between 40 and 100 m²/d but values of over 1500 m²/d have been obtained. Specific yields are relatively high, being about 2%. Water levels in this aquifer vary depending on topography, ranging from near the surface to depths of over 20 m. Substantial portions of the aguifer are confined.

The aquifers often underlie ground that is elevated relative to other rock types, for example, karstified limestones. The volcanic rocks are very resistant to erosion, as are some of the sandstones and the chertier limestones. The weakly-cemented (crumbly) sandstones (the Kiltorcan-type Sandstones) are the exception, and can underlie flat-lying areas.

In higher areas, groundwater flow paths may be relatively short (<500 m), with groundwater discharging to springs, rivers and lakes controlled by the topography. In flatter-lying areas, groundwater may flow for several km's. The Kiltorcan-type Sandstones and Westphalian Sandstones form significant confined aquifers overlain by thick shale/mudstone sequences. The tops of these aquifers may be more than 100 m below ground, and residence times of the groundwater, under natural conditions, may be many years.

Groundwater and Surface Water Interaction:

There are occasional large (>2000 m³/d) springs, particularly in lower-lying areas. Fault zones may influence the locations of the springs, which tend to be dependable. Rivers crossing these aquifers are generally gaining, providing the subsoil or overlying rock layers are not too thick to prevent groundwater discharging to surface water. Baseflow ranges from moderate to substantial. Hydrographs may be 'peaky' with rapid response to rainfall. Dry weather flows can range from 0.5 l/s/km² to about 3 l/s/km².

Groundwater Flooding:

In general, areas underlain by these aquifers are not prone to flooding because the aquifers typically have sufficient storage and transmissivity to mitigate the impact of prolonged and intense rainfall. However, in very low-lying areas the water table may be sufficiently close to the ground surface that groundwater could impact on buried structures and services. There is no written or verbal evidence that this has ever occurred.



Regionally and Locally Important Sand and Gravel Aquifers Rg and Lg:

General Hydrogeological Description:

Sand and Gravel aquifers are predominantly glacio-fluvial deposits such as outwash fans/deltas and eskers, but alluvial deposits adjacent to substantial rivers and ancient alluvial deposits infilling buried valleys also occur. Other types of deposit, such as raised beaches or dune sands, may also form aquifers but at a very local scale. A deposit belongs to the Rg aquifer class if it is highly permeable, more than 10 m thick or has a saturated thickness of at least 5 m, and an area of at least 10 km². Lg aquifers have areas of 1 to 10 km². The principal Rg aquifers are the **Roscrea Gravel** and the Sand and Gravel of **Mid Kildare**, the **Barrow Valley**, the **Nore River**, the **Kilmanagh River** and north of Wexford. Permeabilities, porosities and specific yields depend on grain size, sorting, and the proportion of interbedded silts and clays. Permeabilities generally range between 10 to 80 m/d, porosities between 10 and 40% and specific yields between 5 and 15%. Depths to the water table are generally shallow and often within about 2 m of the ground surface [Tedd et al 2009]. Seasonal variations in groundwater level are small.

Glacio-fluvial deposits tend to be elevated by 5 to 50 m above the surrounding countryside with surfaces that are hummocky, undulating, or flat-topped and steep-sided. In contrast, alluvial sand and gravel tends to form flat deposits that infill the topography along valley bottoms.

The combination of shallow hydraulic gradients and high specific yields means that groundwater velocities are generally slow. Flow path lengths are limited more by the areal extent of the aquifers than by any other parameter. Since Lg aquifers are less than 10 km² in area, flow paths will rarely be more than a couple of kilometres long.

Groundwater and Surface Water Interaction:

The interaction between surface water and groundwater depends on the elevation of the water table relative to that of the river stage and will not be uniform over the area of the aquifer. Groundwater will move into the river to form baseflow at times when the water table is relatively high, but river water will pass into the aquifer when the water table is relatively low. In higher valleys where rivers flow onto the aquifer having previously flowed over impermeable subsoil or bedrock, some surface water will probably pass into the aquifer. At lower elevations there is likely to be groundwater seepage from the extremities of the sand and gravel body, as springs, seeps or a rise in baseflow to the rivers. Water may also come to the surface where there is a barrier to groundwater flow, e.g. a less permeable layer of till within the aquifer. There are often large (>2000 m³/d) springs in these aquifers, particularly in lower-lying areas or at topographic breaks. Rivers bounded by sand and gravel aquifers have substantial baseflows and dry weather flows, and are not 'flashy'. Hydrographs are smooth and vary slowly due to the high aquifer porosity (storage) and bank storage phenomenon. Surface runoff is generally very low over the deposits, due to their high permeability.

Groundwater Flooding:

Areas underlain by sand and gravel aquifers are not prone to groundwater flooding because the aquifers have very large storage capacities due to their high porosities. Flooding does not occur despite the fact that groundwater levels are often within about 2 m of the ground surface. However, in very low-lying areas the water table may be sufficiently close to the ground surface that groundwater could impact on buried structures and services. There is no written or verbal evidence that this has ever occurred. The only known detailed study of potential groundwater flooding investigated the sand and gravel aquifer associated with the Lee River (north and south) in Cork City [Halcrow 2007]. No evidence of such flooding was found, although it was recognised that this could potentially occur, most probably through the hydraulic transfer of pressure waves caused by high tides.



Locally Important and Poor Aquifers, LI, PI and Pu:

General Hydrogeological Description:

Groundwater flows through the subsurface via fractures and faults which originated during the deformation of the rock mass by large-scale compression (folding and mountain-building) or extension (rift valley development). Fracturing can also result from non-structural effects; e.g. stress relief after deep burial, the release of surface pressure after glaciation, frost shattering during and after the ice ages, and more recent processes (e.g. cracking by tree roots). Excepting the top few metres where the rocks are more fractured and/or weathered, the fissures are poorly connected. Hence, the rocks have a low fissure permeability, which tends to decrease rapidly with depth. Greater permeabilities may exist in zones of limited width or thickness, e.g. along major fault zones. These aquifers comprise a variety of rocks including impure limestones, unbedded pure limestones, sandstones, shales, greywackes, slates, granites, basalts, gneisses and schists. There may be limited karstification within the limestones.

Most of the rock types underlie elevated ground. For example, the greywackes and sandstones form the cores of anticlinal (∩-shaped) folds in upland areas. Extensive areas of granite also form high ground (for example, Wicklow Mountains and Connacht). Exceptions to this are the impure and unbedded limestones which often underlie very flat-lying, featureless ground (for example in Westmeath and Offaly).

Flow paths are generally restricted to a few tens to a few hundred metres in length.

Groundwater and Surface Water Interaction:

Surface runoff from locally important and poor aquifers is generally high because their low permeabilities prevent the downward movement of water. Recharge that does penetrate below ground level often discharges quite rapidly to surface waters, springs and seeps, via shallow upper layers. Low storage values means that the aquifers cannot sustain summer baseflows. Springs and upland seeps often dry up or have significantly diminished flows in summer. Baseflows are low and surface water hydrographs are peaky showing a rapid response to rainfall and short recession curves. Upland areas are characterised by high runoff and high drainage densities. This is a function of the low aquifer permeability and recharge acceptance, but is also related to the higher rainfall in upland areas. The high natural drainage densities of lowland areas have been increased by drainage ditches which are a very common feature of the landscape underlain by these rocks.

Groundwater Flooding:

Groundwater flooding does not occur in upland areas because the low permeabilities of these aquifers mean that prolonged and intense rainfall runs off the land surface rather than being absorbed. In low-lying areas the water table is generally near the ground surface, especially in winter when the aquifer's limited porosity and permeability may lead to waterlogging. However, these areas are only of very local extent.



Appendix E. Stage 2 of Methodology, Analysis of Turloughs

ID ¹	Turlough	Easting	Northing	Base Elevation of Turlough (mAOD) ²	Elevation of Flood Extent (mAOD) ³	Difference in Elevation (turlough base to max flood extent, mAOD)
6	Ballymachill Lough	136980	180120	12.82	14.39	1.58
11	Bunakippaun	138960	197600	16.74	19.94	3.20
12	Cappagh Lough	136660	181120	12.99	19.45	6.46
13	Cappagh Lough North	136500	181690	12.86	16.32	3.45
14	Carran (Carran/Fahee)	128200	198560	110.59	119.28	8.69
15	Castle Lough	134520	198230	23.80	24.76	0.96
16	Cloonleen Lough	134100	182520	6.90	9.81	2.91
17	Coolreash East	133300	194390	20.34	20.74	0.40
18	Coolreash Lough	132950	194480	19.20	24.62	5.42
25	Fahee/Carran Turlough (part of Carran overall turlough)	129624	199314	111.16	117.13	5.98
27	Gortalecka B	131900	195000	28.10	38.16	10.06
30	Inishmore 1	135240	184550	11.18	13.86	2.68
31	Inishmore 2	135320	184850	10.50	14.91	4.41
35	Knockaunroe B	130700	193450	26.30	35.47	9.17
36	Knockaunroe Turlough A	131400	194180	26.56	35.47	8.91
40	Lough Avagher	134080	187880	12.00	14.17	2.17
43	Lough Gealain (Gortalecka A)	131450	194730	26.90	32.14	5.24
49	Mullagmore Turlough	131100	194880	27.60	36.49	8.89
50	Nooan/Lough Reagh	132270	185310	13.63	17.25	3.62
57	Rockforest Lough	135770	195400	16.02	19.66	3.64
61	Travaun/Skaghard	135200	196850	18.10	23.46	5.37
63	Tulla	136610	202210	9.41	21.35	11.94
66	Turloughmore (Burren)	134700	199800	27.06	32.72	5.67
113	Callow Lough	172150	234400	85.20	87.30	2.10
121	Carrowholla	167430	233750	90.73	94.80	4.07
135	Cornananta More	176470	247240	47.74	49.60	1.86
163	Gallagher's Wood Turlough	182380	204200	49.12	53.20	4.08
164	Gallagher's Wood West	181880	203950	47.01	47.60	0.59
173	Hillswood	171252	232658	94.69	98.70	4.01
190	Lackan 2 (B)/Cregaclare North	147931	212808	29.71	33.50	3.79
206	Lydacan (South)	143834	207583	11.61	15.50	3.89
214	Parkslevabaun	148396	217192	25.53	30.00	4.47

¹ ID as per the spreadsheet Turloughs_Consolidated_Final_a.xls provided by GIS

² As derived from DTM topographical contours

³ As derived from DTM topographical contours



ID^1	Turlough	Easting	Northing	Base Elevation of Turlough (mAOD) ²	Elevation of Flood Extent (mAOD) ³	Difference in Elevation (turlough base to max flood extent, mAOD)
221	Raheen	144420	207280	11.81	15.50	3.69
223	Roo West Turlough	138627	202214	10.47	19.76	9.29
268	Cordara Turlough	202820	263590	46.90	50.39	3.49
269	Fortwilliam Turlough	201500	263160	42.05	46.07	4.01
270	Thureen/Carrigeens	201570	265100	48.91	52.46	3.55
368	Annaghmore (east of Nablasbarnagh)	189870	283591	47.80	62.27	14.47
370	Ardkillin Lough	188013	278371	47.20	51.01	3.81
373	Ballinlig/Coolmeen	182100	261380	52.19	58.32	6.13
374	Ballinturley	184820	260100	48.87	58.10	9.23
375	Ballygalda Turlough	185200	260800	48.65	57.13	8.48
376	Ballymacurley South	181700	271600	72.75	80.44	7.70
378	Bloomfield	187120	279240	48.30	56.17	7.87
380	Brierfield Turlough	181600	276560	91.40	97.31	5.92
382	Carrowduff and Garbally	192200	238800	53.60	55.40	1.80
383	Carrowkeel Turlough Roscommon	184350	261550	48.66	56.70	8.04
390	Castlesampson	191840	240360	53.28	54.80	1.52
392	Cloonfree Lough	191000	279600	46.00	55.90	9.90
393	Cloonloughlin/Four R	183710	251620	48.74	53.49	4.75
396	Corbally Turlough	184900	280160	61.94	65.21	3.27
397	Corkip Lough	192840	243470	55.25	55.60	0.35
398	Corrabeg/turlough w of Corbally house	186200	280100	54.86	56.85	1.98
399	Cuileenirwan/Coolagarry Loughs	188800	246520	65.12	65.50	0.38
402	Feacle Lough	190790	243390	58.00	62.50	4.50
403	Feevagh complex	184170	242620	40.55	45.58	5.03
404	Fin Lough	189800	278400	46.20	55.78	9.58
406	Glennanea	190070	238170	52.12	54.00	1.88
409	Keenagh	182980	256080	48.26	50.63	2.37
410	Keenagh North	182528	257098	47.19	53.19	6.00
413	Kinnity Roscommon	184810	272430	73.42	83.33	9.91
416	Lisduff	184250	255500	48.98	57.21	8.24
417	Lismurtagh	180850	277930	93.70	98.69	4.98
419	Lissonuffy	193290	277050	45.89	52.25	6.36
421	Lough Conny More Complex	186750	282300	48.80	51.85	3.05
422	Lough Croan	187430	249830	67.46	71.33	3.87
423	Lough Cup	195450	249640	65.20	70.61	5.41
424	Lough Funshinagh	193350	251450	63.94	73.69	9.75
427	Loughnaneane Turlough	186850	264900	51.28	54.52	3.24
431	Pound Hill	197030	247950	60.25	70.70	10.45
433	Shad Lough	182600	275700	78.30	80.90	2.60



ID¹	Turlough	Easting	Northing	Base Elevation of Turlough (mAOD) ²	Elevation of Flood Extent (mAOD) ³	Difference in Elevation (turlough base to max flood extent, mAOD)
434	Stonepark Turlough	185200	262350	49.28	54.13	4.85
436	Toomona House turlough	181600	280000	74.61	82.95	8.34
437	Turlagh A	192350	253920	70.97	72.87	1.90
438	Turlaghmore	191000	238600	53.10	55.90	2.80
469	Cornaling Lough	186060	192920	45.13	50.50	5.37
471	Kyleomadaun	187600	191400	55.10	56.40	1.30
472	Liskeenan	196620	198360	63.03	64.30	1.27
473	Lismaine	196180	195700	66.25	67.10	0.85
474	Newchapel Turlough	185370	192520	44.11	48.10	3.99
475	Oldcourt	186730	193560	48.55	51.20	2.65
479	Rahinane (Ballingarry)	196850	196400	66.73	67.50	0.77
480	Rodeen Lough	188250	193100	54.00	54.10	0.10
481	Sluggary Pool	195420	202560	58.12	59.00	0.88
482	Spring Park Wetlands	190300	198000	55.14	56.30	1.16



Appendix F. Turlough Information

There are 37 flood events associated with turloughs on www.floodmaps.ie for which there are readily accessible reports containing useful information such as details of the flood extent, its location and, in some cases, photographs. The relevant turloughs are listed below.

Flood ID	Flood Name	X Coordinate	Y Coordinate
382	Turlough - Lough Nakill Mocolloghan Shrule Mayo	125985	254209
628	Turlough - Cummer, Galway	140312	246485
752	Turlough - Knockaunroe A, Clare	131 400	194180
813	Turlough - Carrowreagh/Rahardagh, Roscommon	178378	275305
814	Turlough - Mullygollan/Carrownaskeagh, Roscommon	179780	279400
818	Turlough - Castleplunket, Roscommon	177670	277840
820	Turlough - Rathnalulleagh, Roscommon	177710	273760
829	Turlough - Roo Demesne, Galway	133460	209810
968	Turlough - Turloughnarorey or Common, Galway	138009	249911
971	Turlough - Hawkhill, Knockaunatouk, Galway	141140	202320
991	Turlough - Killeeneen More, Galway	146818	219100
993	Turlough - Castlegar, Galway	143640	218340
994	Turlough - Dunkellin, Roevehagh, Galway	144700	218800
1002	Turlough - Rahasane, Rahasane/Carrigeen West	147851	219635
1013	Turlough - Corrandrum, Galway	141270	240750
1052	Turlough - Turloughaclara, Thomastown, Mayo	123422	260874
1065	Turlough - Agurkall, Clyard Ballynacarragh	123500	259200
1094	Turlough - Coole Lough, Coole Demesne, Galway	143110	204260
1095	Turlough - Caherglassaun, Killomoran, Galway	141456	206290
1121	Turlough - Fortwilliam Turlough, Commons, Longford	201500	263160
1478	Coole Area South Galway March 1994	141 051	202513
1479	Ballylee Area South Galway March 1994	148904	206086
1480	Blackrock Area South Galway March 1994	149917	207840
1481	Tullaghnafrankagh area South Galway March 1994	143400	215440
1482	Mannin Cross area South Galway March 1994	149227	217297
1543	Turlough - Lough Coy, Galway	148927	207255
1644	Turlough - Tullaghnafrankagh Caherpeak West Galway	143208	215339
1647	Turlough - Ballylee River, Cloonanearla, Galway	147864	206395
1654	Turlough - Curragh Lough, Beagh, Galway	156382	267733
1924	Rashane Recurring	148488	219845
1956	Gort Area Caherglassaun Jan 1995	141 456	206290
2194	Termon Area South Galway Recurring	141 485	197737
2236	Blackrock Area South Galway Jan 2000	149917	207840
2285	Ballybackagh Bullaunagh, Galway 1995	151687	210206
3059	Rahasane Turloughs Shanbally Castle Jan 2005	148488	219845
10402	Turloughmartin Dec 2006	150750	222350
10440	Turlough, Fortwilliam Turlough, Cashelbeg, Lanesborough, Co. Longford Dec 06 - Feb 07	201500	263160