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Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Combining earth observation and geochemical tracing techniques for groundwater detection and evaluation in Ireland

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Comhshaol, Pobal agus Rialtas Áitiúil
Environment, Community and Local Government

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Combining Earth Observation and Geochemical Tracing Techniques for Groundwater Detection and Evaluation in Ireland (CONNECT)

(2012-W-MS-13)

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Prepared for the Environmental Protection Agency

by

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

Precipitation that reaches the earth's surface can infiltrate into the ground to become groundwater. Groundwater is subsurface water that fully saturates pores or cracks in soil and rocks. While an important source of freshwater globally, groundwater is also environmentally important as baseflow or low-water flow, which maintains river, stream and lake levels, as well as their associated ecosystems. *Groundwater discharge* is the movement of water *out* of an area of saturated soil and *groundwater flow* is the movement of water that travels and seeps *through* soil and rock underground. Groundwater in transit can become contaminated with a variety of substances from above and below the land surface, including nutrients and heavy metals. As surface water is typically hydraulically connected to groundwater, nearly all surface-water features interact with groundwater. This means that groundwater discharge is a significant source and pathway of freshwater and solute transfer to surface-water features, particularly when originating from contaminated aquifers.

Groundwater discharge is potentially a significant source of contamination to surface-water features in Ireland, which has implications for the type and extent of monitoring required to fulfil national and international environmental policy objectives, such as those defined under the Water Framework Directive (WFD, Directive 2000/60/EC). The WFD is the most important piece of EU legislation governing the sustainable management of water across Member States. The Environmental Protection Agency (EPA) has implemented individual monitoring programmes for groundwater and surface water to provide an assessment of overall water status, as well as to identify water bodies "at risk" of failing to meet WFD environmental targets. The WFD also requires integrated management of groundwater and surface-water resources, which necessitates an improved understanding of surface water–groundwater exchange processes. Groundwater discharge and associated nutrient loading via groundwater discharge remains a poorly understood process, particularly when implementing water monitoring and management programmes. This is because groundwater discharge is highly variable, both spatially and temporally, and identifying where and how much groundwater discharge is occurring is an extremely challenging task. While Irish groundwater risk assessments for WFD have taken contaminant transfer to surface waters into account in some instances (e.g. phosphorus transfer to rivers) (Daly, 2009), direct groundwater discharge to lakes and coastal waters has not been specifically addressed to date.

In recognition of this knowledge gap and the implications for water management practices, the CONNECT project (combining earth observation and geochemical tracing techniques for groundwater detection and evaluation in Ireland) was funded as part of the EPA research programme. The overall goal of the project was to develop tools to facilitate a national assessment of groundwater discharge to lake and coastal waters in Ireland, and a three-tiered approach was adopted to meet the objectives of the research. A national geographical analysis of all lake and transitional and coastal (TRAC) water bodies was completed as part of the first approach, using datasets describing groundwater–surface water connectivity. The aim was to classify each surface-water feature by its likelihood of receiving groundwater discharge, which was defined relative to a number of simple criteria, including underlying aquifer type, presence of geological faults, springs and other karst features. The key output was a national map of likelihood of groundwater discharge, which was then used to inform the acquisition of thermal imagery as part of the second approach.

Remote sensing is the science of acquiring information about objects on the earth's surface or in the atmosphere without being in direct contact with those objects, and recent advances in remote sensing provide an affordable tool with which to detect and evaluate the impact of groundwater discharge to surface waters. Temperature has been used very successfully to study groundwater discharge by comparing the relatively constant temperature of groundwater with that of surface waters, which fluctuate with season. In Ireland, during the summer months, groundwater discharge manifests within satellite imagery as a cool thermal signal relative to receiving waters and, as part of the second approach, surface water temperature and temperature anomaly maps were generated using satellite imagery to detect thermal signals potentially indicative of groundwater

discharges. The maps were also used to verify the likelihood classification. The study revealed that larger (more negative) thermal anomaly values were present in higher likelihood water bodies than in lower likelihood water bodies. The results from the first and second approaches were used to guide the identification of a number of target regions for detailed *in situ* analyses of groundwater processes as part of the third approach.

A natural environmental tracer of groundwater discharge, radon-222 (^{222}Rn), was used to complete both qualitative and quantitative analyses of groundwater discharge at eight target sites as part of the third and final approach. Radon is present in most rocks and dissolves into groundwater held within aquifers. The distinctive and measurable difference that exists between radon concentrations in groundwater relative to surface water is the fundamental basis for using radon to trace groundwater discharge. When radon-rich groundwater is exposed to the atmosphere, any radon present degasses immediately, which produces a very sharp concentration gradient at the groundwater–surface water interface. Radon activity concentrations were measured to expose radon "hotspots" as localised groundwater entry points and to provide quantitative estimates of groundwater discharge rates.

Research completed as part of the CONNECT project endeavours to address knowledge gaps in field-based scientific information on the interaction between groundwater, lakes and coastal areas. The outputs presented in this report could potentially be used to inform and guide any future studies seeking to localise and quantify groundwater discharge and associated nutrient loading to surface-water features. This is particularly pertinent in the light of second-cycle WFD requirements, which include the development of actions, such as drafting environmental objectives, undertaking catchment characterisation, preparing river basin management plans (RBMPs) and programmes of measures (POMs), to gather better information and expand our knowledge of the aquatic environment.

1 Introduction

1.1 Background to the Study

Groundwater is subsurface water that fully saturates pores or cracks in soil and rocks. The underground layer of water-bearing permeable rock, rock fractures or unconsolidated material (e.g. gravel, sand and silt) is called an aquifer. Groundwater constitutes the largest reservoir of freshwater in the world, accounting for over 97% of all available freshwater (excluding glaciers and icecaps) (EC, 2012). Groundwater is an important resource and is being increasingly exploited to meet global demands for drinking water, agriculture and industry. Groundwater is also environmentally important as baseflow, which maintains wetlands, surface-water systems (e.g. lake levels and river flows) and their associated terrestrial and aquatic ecosystems.

Groundwater discharge is the movement of water *out* of an area of saturated soil: more specifically, it is the volumetric flow rate of groundwater through an aquifer. Groundwater flow is the movement of water that travels and seeps *through* soil and rock underground, which can become contaminated with a variety of substances from above and below the land surface in transit, including nutrients and heavy metals. Surface water is typically hydraulically connected to groundwater, which means that nearly all surface-water features, such as lakes, reservoirs, streams, rivers and estuaries, interact with groundwater (Winter *et al*., 1998). Surface-water features can gain water and solutes from groundwater systems; equally, surface-water features can act as sources of groundwater recharge via seepage to adjacent aquifers. This means that pollution of surface-water features can cause deterioration in groundwater quality and conversely pollution of groundwater can degrade surface-water systems. Groundwater discharge, therefore, is a significant pathway of freshwater and solute transfer to surface-water features, particularly when originating from contaminated aquifers (Slomp and Van Cappellen, 2004). The interaction between groundwater and surface water can impact water chemistry, water quality, biology and ecology (Shaw *et al*., 2013) and a number of studies have identified groundwater discharge as one of the main drivers of eutrophication in lakes (Paerl, 1997; Zhu and Schwartz, 2011; Robinson, 2015). Groundwater has also been highlighted as a potential precursor of harmful algal blooms in nearshore waters (Anderson, 2009).

Groundwater is potentially a significant source of contaminants to surface-water features in Ireland, which has implications for the type and extent of monitoring required to fulfil national and international environmental policy objectives, such as those defined under the Water Framework Directive (WFD, Directive 2000/60/EEC). The WFD is the most important piece of EU legislation governing the sustainable management of water and associated wildlife and habitats. EU Member States must establish a programme to monitor water status in order to achieve the objectives of the WFD, which include the attainment and retention of “good status” (i.e. both good chemical and good ecological status) or better (EC, 2000).

In Ireland, national coordination of all of the technical aspects of the WFD is the responsibility of the Irish Environmental Protection Agency (EPA). The EPA has implemented individual monitoring programmes for groundwater and surface water to provide an assessment of overall water status, as well as to identify water bodies “at risk” of failing to meet WFD environmental targets (EPA, 2006). The WFD also requires integrated management of water resources, which necessitates an improved understanding of surface water–groundwater exchange processes. Internationally, water resource managers have begun to incorporate management strategies that require quantifying flow between surface and groundwater (Brodie *et al*., 2007). Groundwater discharge and associated nutrient loading via groundwater discharge, however, remain poorly understood processes when implementing water monitoring and management programmes in Ireland. This is because groundwater discharge is highly variable, both spatially and temporally, and identifying where and how much groundwater discharge is occurring is an extremely challenging task. Irish groundwater body risk assessments for WFD have taken contaminant transfer to surface waters into account in some instances (e.g. phosphorus transfer to rivers) (Daly, 2009), but direct groundwater discharge to lakes and coastal waters has not been specifically addressed to date.

In recognition of this knowledge gap and the implications for water management practices, the CONNECT[1] project was funded as part of the EPA research programme (2007–2013). The 2.5-year project aimed to complete a national assessment of groundwater discharge to lake and coastal waters in Ireland.

1.2 Project Aims and Objectives

The overall goal of CONNECT was to develop tools to facilitate a national assessment of groundwater discharge to lakes and coastal waters in Ireland. A three-tiered approach was adopted to meet the objectives of this research project, which incorporated geographical information system (GIS), remote sensing and geochemical tracing analyses.

1.2.1 Approach 1 – geographical information system analyses

A national geographical analysis of lake and transitional and coastal (TRAC) water bodies was completed within a GIS using spatial datasets describing groundwater–surface water connectivity. The aim was to classify each surface-water feature by its likelihood of receiving groundwater discharge. Each lake and TRAC water body was evaluated relative to a number of simple criteria describing local geology. The key output from this preliminary approach was a national map of likelihood of groundwater discharge, which was used to guide the acquisition of thermal imagery as part of the second approach.

1.2.2 Approach 2 – remote sensing analyses

Remote sensing (Campbell and Wynne, 2012) is the science of acquiring information about objects on the earth's surface or in the atmosphere without being in direct contact with those objects, and recent advances in remote sensing provide an affordable tool with which to detect and evaluate the impact of groundwater discharge to surface waters. Temperature has been used very successfully to study groundwater discharge by comparing the relatively constant temperature of groundwater with that of surface waters, which fluctuate with season. In Ireland, during summer months, groundwater discharge manifests as a cool thermal signal relative to receiving waters (Wilson and Rocha, 2012, 2016). The aim of the second approach, therefore, was to use remote sensing to detect thermal signals potentially indicative of groundwater discharge to surface-water bodies.

Surface water temperature and temperature anomaly maps were generated from freely available satellite thermal imagery for lakes and TRAC water bodies across Ireland. The maps were also used to verify the likelihood of groundwater discharge. The study revealed that larger (more negative) thermal anomaly values were present in higher likelihood water bodies than in lower likelihood water bodies. The results from the first and second approaches were used to guide the identification of a number of target regions for detailed *in situ* analyses of groundwater processes as part of the third approach.

1.2.3 Approach 3 – geochemical tracing analyses

The aim of the third approach was to complete both qualitative and quantitative analyses of groundwater discharge using a natural geochemical tracer of groundwater, radon-222 (^{222}Rn), at a number of target sites. Eight lakes were selected to meet the objectives of the third approach. The distinctive and measurable difference that exists between radon concentrations in groundwater relative to surface water is the fundamental basis for using radon to trace groundwater discharge to surface-water bodies. Radon is present in most rocks and dissolves into groundwater held within aquifers. It is a radioactive and conservative gas with a half-life of 3.82 days. When radon-rich groundwater is exposed to the atmosphere, any radon present degasses immediately, which produces a very sharp concentration gradient at the groundwater–surface water interface. Surface water radon activity concentrations were measured during a survey of the lakes to expose radon "hotspots" as localised groundwater entry points. The results from the lake radon surveys were also used to produce quantitative estimates of total groundwater discharge rates, as the sum of both direct and indirect groundwater discharge. Direct groundwater discharge is defined as the subterranean or pure component of groundwater discharge, i.e. groundwater that seeps directly from the aquifer into the lake. Indirect groundwater discharge is the groundwater component of rivers and streams that discharge into the lake.

1 Combining earth observation and geochemical tracing techniques for groundwater detection and evaluation in Ireland, EPA Project Code: 2012-W-MS-13.

Research completed as part of the CONNECT project endeavours to address key knowledge gaps in field-based scientific information on the interaction between groundwater, lakes and coastal waters in Ireland. The outputs presented in this report can potentially be used to inform and guide any future studies seeking to localise and quantify groundwater discharge and associated nutrient loading to surface-water features. This is particularly important in light of the EPA's integrated catchment[2] management (ICM) strategy, an approach that is providing the national framework for more effective and sustainable water management as part of the second cycle of the WFD (Daly *et al*., 2014). ICM necessitates a holistic and integrated approach to the management of land, biodiversity, water and community resources at the catchment scale (Williams, 2012). According to Daly *et al.* (2014), ICM requires catchments to be viewed in three dimensions to facilitate a full and complete understanding of where water comes from and how it moves above, below and through the landscape. An ICM approach is necessary to elucidate sources and pathways of contamination within a catchment allowing the activities causing pollution to be identified and managed more effectively. With continued provision of evidence-based scientific information at the local or water body scale, as provided here, the EPA will be better equipped to draft environmental objectives, complete catchment characterisation and prepare river basin management plans (RBMPs) and programmes of measures (POMs) using "better knowledge" of the aquatic environment (DECLG, 2015) as per the second-cycle WFD requirements.

2 A catchment can be defined simply as the geographical area contributing water to a river and its tributaries with all the water draining ultimately to a single outlet (e.g. lake, estuary).

2 Methodology

2.1 Overview

The goal of CONNECT was to develop tools to facilitate a national assessment of groundwater discharge to lake and coastal waters in Ireland. A three-tiered approach was adopted to meet the objectives of this research project, which incorporated GIS, remote sensing and geochemical tracing analyses. Specifically, the project sought to:

1. Complete a national characterisation of the likelihood of a water body (lake and TRAC) to receive groundwater discharge.
    (a) Map the spatial distribution of lakes and TRAC water bodies by likelihood.
    (b) Use the likelihood classification to guide the acquisition of thermal imagery as part of the second approach.
2. Create surface temperature and temperature anomaly maps using satellite imagery to detect thermal signals potentially indicative of groundwater discharge to lakes and TRAC water bodies.
    (a) Use the thermal maps to localise sites of potential groundwater discharge.
    (b) Use the temperature anomaly maps to verify the likelihood classification.
3. Localise groundwater discharge entry points and estimate groundwater discharge rates for eight target sites, using radon as a natural environmental tracer of groundwater.

2.2 National Characterisation of Likelihood of Groundwater Discharge using a Geographical Information System

2.2.1 Methodological approach

The starting point for the national characterisation of likelihood of groundwater discharge was the groundwater body unit. A groundwater body is a distinct spatial unit that describes the geographic position and extent of an aquifer or group of aquifers. The GIS analysis was based on the groundwater body as opposed to the catchment because surface-water catchments are typically defined based on surface-water hydrology and topographic divides, which may not coincide with groundwater catchments.

A national groundwater body map (Figure 2.1) was created by the Geological Survey of Ireland (GSI) as part of the requirements of the WFD to facilitate more effective monitoring and managing of groundwater resources (Hunter-Williams *et al*., 2011). Large geographical areas of an aquifer or groups of aquifers were divided into distinctive units by the GSI based on groundwater flow regime and major hydrological boundaries with the assumption that groundwater flow between the groundwater bodies is negligible.

The GSI's groundwater body classification recognises four aquifer types pertaining to the predominant transfer pathway of groundwater through a groundwater body. For instance, groundwater bodies are described as (a) karstic (K), where groundwater flows through fissures and conduits in karstified limestone, (b) productive fissured (PF), where flow is along fissures in bedrock, and (c) sand and gravel (SG) aquifers, where flow is between sand and gravel grains. Poorly productive (PP) aquifers are considered generally unproductive with low transmissivity and low effective porosity (meaning the pore spaces within the aquifer are not very big).

For this study, likelihood of groundwater discharge was defined on the basis of simple criteria (Figure 2.2), which addressed, sequentially, the impact of aquifer type, the presence of geological faults, springs and other karst features, as well as subsoil permeability,[3] on the movement of groundwater into a lake or TRAC water body. These criteria were selected because geological faults typically facilitate the flow of groundwater, while the presence of springs and karst features indicates that groundwater is reaching the surface at that location. Therefore, the likelihood of a surface-water body receiving groundwater discharge is considered greater where faults, springs or karst features are adjacent to or in close proximity to a lake or TRAC water

3 Subsoil permeability describes how groundwater moves through the soil; low subsoil permeability indicates that the soil does not transmit groundwater freely.

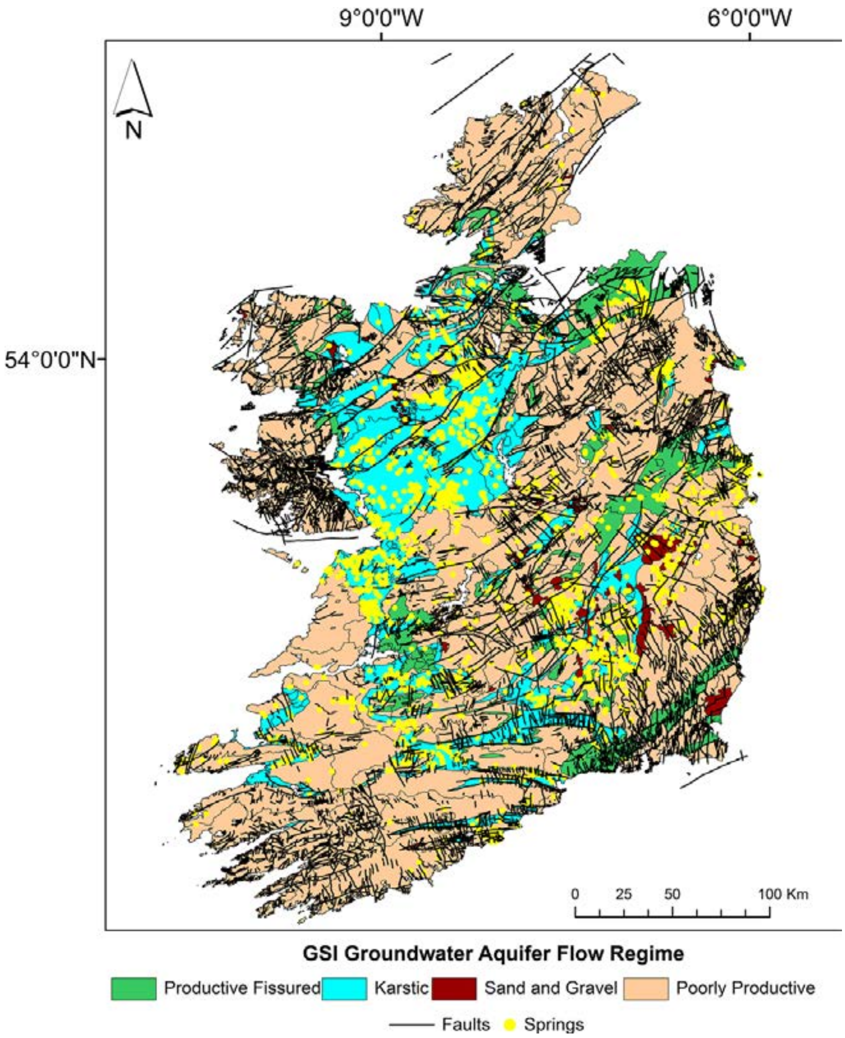

Figure 2.1. National groundwater body map illustrating the spatial distribution of karstic, productive fissured, sand and gravel and poorly productive aquifers across Ireland and national distribution of faults (black lines) and springs (yellow dots).

body. Conversely, the presence of low permeability subsoils act as a barrier or impediment to the movement of groundwater. The geographical datasets describing the criteria detailed above are available at the national scale and can be visualised as well as downloaded for use, free of cost, via EPA (gis.epa.ie/envision) and GSI (GSI Spatial Data) online map viewers.

The analysis was completed at three scales in order to refine the likelihood classification by giving full consideration to each of the criteria at every step in the classification process.

2.2.2 Likelihood rationale

At scale 1 (Figure 2.2), aquifer type was the only likelihood criteria, and lakes and TRAC water bodies were classified as either "more likely" or "less likely" on the basis of whether they were underlain by productive aquifers (collectively all of the karstic, productive fissured and sand and gravel aquifers) or poorly productive aquifers.

At scale 2, the likelihood criteria included the presence of springs and faults. For instance, scale 1 "more likely" lakes and TRAC water bodies with either a spring and/or a fault within a 1 km distance from the water body boundary were classified as "very high" or "high", respectively. scale 1 "more likely" lakes and TRAC water bodies with neither a spring nor a fault in the vicinity were classified as "moderate" likelihood at scale 2. Finally, scale 1 "less likely" lakes and TRAC water bodies with a fault within a 1 km distance from the water body were classified as "less likely", while those without faults were classified as "least likely" at scale 2.

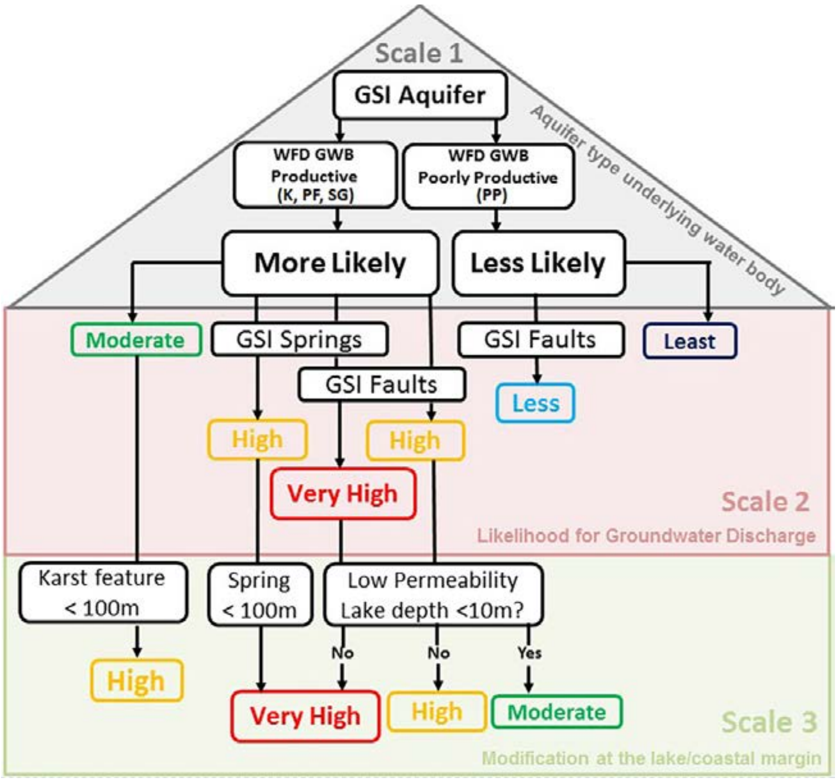

Figure 2.2. Schematic illustration summarising the likelihood of groundwater discharge classification. Likelihood is described by the categories "very high", "high", "moderate", "less" and "least", and corresponds to analyses undertaken across three scales (scale 1, scale 2 and scale 3).

At scale 3, subsoil permeability was included as an additional criterion for lakes. For example, scale 2 "very high" or "high" likelihood lakes with mean water depths less than 5 m, were reclassified as "moderate" likelihood if surrounded by thick (>10 m), low permeability subsoils. In addition, scale 2 "moderate" likelihood lakes or TRAC water bodies were further evaluated against the karst database of the GSI. Lakes or TRAC water bodies within 100 m of a karst feature (including swallow holes, caves, enclosed depressions, dry valleys and superficial solution features, but not boreholes) were reclassified from "moderate" to "high" likelihood at scale 3. This step was undertaken in an effort to address the limitations of the springs and faults databases, which are incomplete, in other words not fully representative nationally.

In addition, scale 2 "high" likelihood lakes and TRAC water bodies were awarded "very high" likelihood at scale 3, where mapped springs or faults fell within 100 m of the water body margin. Finally, on the basis of conducted and published research and the combined experience of the research team and Steering Committee, a number of lake or TRAC water bodies were assigned a higher likelihood (e.g. from "moderate" to "high" or "very high" likelihood) where it was observed and subsequently agreed upon that the national spatial datasets employed had failed to highlight a particular water body that is known to host groundwater discharge.

2.3 National Assessment of Groundwater Discharge using Remote Sensing

2.3.1 Methodological approach

In practice, and in particular from a lakes perspective, the majority of water bodies in Ireland are underlain by either karst or poorly productive aquifers, meaning most of the higher likelihood lakes and TRAC water bodies are underlain by karst aquifers above productive fissured or sand and gravel aquifers, which comprise the minority. As part of this project, the importance of examining sites for which the potential to receive groundwater discharge is less understood is acknowledged. This means that, as part of the remote sensing approach, satellite imagery was acquired and processed, firstly, for the higher likelihood lakes and TRAC water bodies underlain by productive fissured and sand and gravel aquifers,

then, secondly, for a proportionate analysis of karstic water bodies. Furthermore, in order to test the validity of the applied likelihood classification, remote sensing data for a subset of “less” and “least” likely lakes and TRAC water bodies were also examined to compare the evidence from satellite-derived temperature data for groundwater input from poorly productive aquifers. The subset was also chosen to establish whether or not there is evidence that the existing national fault dataset is of any value in identifying groundwater inputs from poorly productive aquifers.

Groundwater–surface water exchanges, including the transfer of pollutants from poorly productive aquifers to lakes and TRAC water bodies, while little studied and poorly understood, are thought to be significant (Moe *et al*., 2010). Poorly productive aquifers are generally considered to transmit and yield very small quantities of water compared with regionally important (e.g. karstified, productive fissured and sand and gravel) aquifers, which, in theory, means that these aquifers are not capable of accepting all of the recharge that might be available from rainfall. Rejected recharge therefore has the potential to enhance discharges to surface water via shallow groundwater pathways and overland flow (Moe *et al*., 2010), which we suggest may manifest within the satellite-derived thermal data for lakes and TRAC water bodies underlain by poorly productive aquifers.

2.3.2 Creating surface temperature and temperature anomaly maps

Traditionally, remote sensing of surface water temperatures has been undertaken using sensors that operate in the infrared (IR) portion of the electromagnetic spectrum, where emissivity of large water surfaces is close to zero. The literature reports on the successful deployment of remote sensing technologies to delineate groundwater discharge to lakes and nearshore environments but mostly with reference to high-resolution airborne (Kelly *et al*., 2013; Lewandowski *et al*., 2013), handheld (Duarte *et al*., 2006) or ground-based thermal imaging systems (Schuetz and Weiler, 2011). These systems, while effective, tend to be extremely costly and certainly not suitable for a regional scale assessment or continued monitoring of groundwater discharges across catchments for water management purposes. The United States Geological Survey (USGS) series of Landsat satellites measure thermal radiation at an appropriate scale to facilitate the study of lakes and TRAC water bodies with excellent coverage across Ireland (Figure 2.3). Moreover, the data are available to

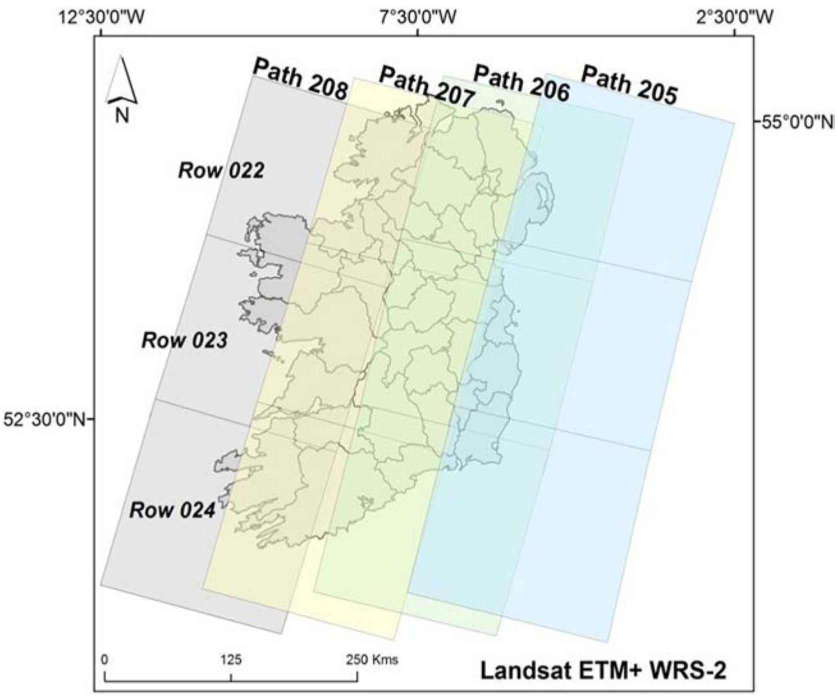

Figure 2.3. Geographical extent and coverage of the USGS Landsat earth observation satellite series for Ireland detailing image footprints by path and row number, as defined by the USGS Landsat World Reference System (WRS) Enhanced Thematic Mapper plus (ETM+).

download for processing free of charge from the USGS GLOVIS (Global Visualisation Viewer) facility (USGS, 2014).

Surface water temperature values were generated from Landsat thermal data (Table 2.1) using commercially available image processing software (ERDAS Imagine Advantage, Hexagon Geospatial, Norcross, GA, USA). The methodology for retrieval of surface temperature from Landsat thermal data is presented in detail in Wilson and Rocha (2012).

Temperature anomaly describes the difference between surface water temperature at a specific location within a water body and the average temperature value recorded across the water body. For each water body, the value for temperature anomaly was used to map standardised temperature anomaly (STA) values, which were calculated by dividing temperature anomaly by the standard deviation of surface water temperature values. Standardised temperature anomaly maps were generated from the surface temperature maps to allow a comparative analysis of lake and TRAC water body surface temperature values generated from satellite imagery acquired on different calendar dates.

2.4 *In Situ* Verification and Evaluation of Groundwater Inputs using Geochemical Tracing Analyses

2.4.1 Methodological approach

Eight target lakes were selected on the basis of a methodological approach leading to the development of four test scenarios (Table 2.2). Lakes were selected that met the test scenario requirements, the number of

Table 2.1. Suite of Landsat thermal imagery of Ireland, acquired to map surface water temperature values

Sensor	Acquisition date	Path/row
Landsat 8 TIRS	9 June 2013	207/022
Landsat 7 ETM+	18 March 2003	207/022
Landsat 8 TIRS	9 June 2013	207/023
Landsat 7 ETM+	19 April 2009	207/023
Landsat 7 ETM+	2 July 2001	207/023
Landsat 7 ETM+	22 July 2000	208/022
Landsat 7 ETM+	22 July 2000	208/023
Landsat 7 EMT+	16 June 2010	208/024
Landsat 7 ETM+	28 August 2001	206/023
Landsat 7 ETM+	24 May 2001	206022
Landsat 8 TIRS	18 April 2014	206/023
Landsat 7 ETM+	24 May 2001	206/023
Landsat 7 ETM+	28 August 2001	206/024
Landsat 7 ETM+	2 June 2010	206/024
Landsat 7 ETM+	8 May 2001	206/024
Landsat 7 ETM+	10 September 2009	206/024

ETM+, Enhanced Thematic Mapper plus; TIRS, Thermal Infrared Sensor.

Table 2.2. Site selection rationale illustrating the link between test scenario, the GIS likelihood for groundwater discharge classification and the remote sensing analyses of surface water temperature. "More likely" refers collectively to the "very high", "high" and "moderate" likelihood lakes. "Less likely" refers collectively to the "less" and "least" likelihood lakes

Test scenario	GIS likelihood classification	Remote sensing evidence
1A	More likely	Plumes evident – large negative anomaly
2B	More likely	No plumes evident – weak negative anomaly
2A	Less likely	Plumes evident – large negative anomaly
2B	Less likely	No plumes evident – weak negative anomaly

which was contingent on the time frame and budget of the project.

2.4.2 Qualitative and quantitative analyses of groundwater discharge using radon

Surveys of surface water radon activity were completed for each of the target lakes between February and May 2015, under dry and calm conditions (Table 2.3). Radon activity concentrations in lake surface water were measured continuously over the course of 1-day surveys to expose radon "hotspots" as part of a qualitative analysis to verify the presence of groundwater and to localise groundwater entry points. The radon activity data was also used to provide quantitative estimates of groundwater discharge rates using a mass balance approach (Appendix 1).

Lake radon measurements were taken by boat using DURRIDGE radon-in-air monitors (DURRIDGE, 2012) combined with a Liqui-Cel® MiniModule® membrane (3M Industrial Group, Minneapolis, MN, USA). Water was pumped from just beneath the lake surface through the membrane, which allows radon to degas from the water column. Radon-rich air travels from the minimodule via tubing into a dehumidifier before entering the radon monitor for measurement (Figure 2.4).

The radon monitoring system was used in tandem with a GPSMAP 750s Sounder (GARMIN, Kansas, TX, USA) for precise location, water depth and water temperature

Table 2.3. Target lakes by test scenario detailing lake survey dates

Test scenario	Lake name	Area (km²)	Groundwater aquifer type	Geographic coordinates (latitude/longitude)	Date surveyed (dd/mm/yyyy)
1A "more likely" Plumes evident	Gur	0.79	Karstic	52.518/–8.533	07/05/2015
	Sheelin	18.16	Karstic	53.803/–7.329	10/04/2015
1B "more likely" No plumes evident	Carrigavantry	0.12	Productive fissured	52.170/–7.199	27/02/2015
	Killinure	0.21	Sand and gravel	53.452/–7.897	06/05/2015
2A "less likely" Plumes evident	Ennell	11.56	Poorly productive	53.469/–7.399	19/03/2015
	Ramor	7.13	Poorly productive	53.814/–7.063	09/04/2015
2B "less likely" No plumes evident	Dan	1.03	Poorly productive	53.069/–6.279	03/02/2015
	Tay	0.50	Poorly productive	53.106/–6.267	04/02/2015

Figure 2.4. Lake survey equipment and boat set-up.

measurements. Water samples were also taken during the survey to assess nutrient concentrations (nitrate, nitrite and ammonium) of the lake and to infer the role of groundwater as a nutrient source by establishing if the radon signal was accompanied by a nutrient signal. To ensure good spatial coverage, samples were drawn from the water surface at regular intervals across the lake. Nutrient concentrations, where possible, were compared against EPA-specified thresholds for surface-water quality (EPA, 2001, 2012).

For each lake, groundwater was sampled to determine the background concentration of radon within the aquifer, which is called the groundwater radon endmember. Samples were drawn from boreholes or springs, where present, and as close to the lake margin as possible.

To substantiate the findings and qualify radon as an effective means to localise and follow groundwater inputs across lakes, spatial analyses were employed. Measured lake radon activity concentrations were plotted using the global positioning system (GPS) data recorded concurrently during the radon survey and subsequently interpolated within a GIS to produce maps of the spatial distribution of measured radon activity. To ensure that the most dominant and consistent pattern of groundwater inputs evident from the radon data are revealed, as well as providing a means for between lake comparisons, standardised radon anomaly (SRA) values[4] were calculated and mapped.

Finally, to ensure good spatial resolution of the lake radon activity data, the boat did not sail faster than 3 knots during the survey. Moreover, the surveys were completed under calm and dry conditions because strong winds lead to increased degassing rates and rainfall may potentially dilute the radon signal in the lake.

4 Standardised radon anomaly (dimensionless) is defined as the difference between the radon activity at each sample point on the lake and the average radon activity of the lake, divided by standard deviation.

3 Results

3.1 National Characterisation of Likelihood of Groundwater Discharge using a Geographical Information System

Over 1000 surface-water features comprising 818 lakes, 193 transitional and 107 coastal bodies were classified according to the likelihood of that water body receiving significant groundwater discharge. The preliminary output following the classification at scale 1 (Figure 2.2) revealed that the "more likely" lakes and TRAC water bodies are underlain predominately by karstic aquifers above productive fissured or sand and gravel aquifers (Table 3.1). Overall, however, poorly productive aquifers underlie the majority of lakes and TRAC water bodies in Ireland (Table 3.1, Figure 3.1).

The final national characterisation of lakes and TRAC water bodies by likelihood of groundwater discharge incorporated criteria that included an evaluation of not only the presence of faults, springs and karst features, but also proximity to these features, and, for lakes, also included an evaluation of the presence of thick (>10 m) low permeability subsoils. Information derived from expert knowledge of the research team and steering committee was also used to inform the final national characterisation.

As part of the interrogation of the karst features database it was discovered that eight lakes in the study were also classified as turloughs (Table 3.2). As these water bodies are clearly groundwater fed as turloughs (while at the same time acknowledging that in some instances these turloughs may have a permanent body of water) they should not be studied as lakes. Consequently, these lakes were removed from the database of results and from further analysis.

Table 3.1. Lake and TRAC water body likelihood of groundwater discharge classification at scale 1 by groundwater body aquifer type

Groundwater body aquifer type	Likelihood classification (scale 1)	Lake	Transitional	Coastal
Karstic	More likely	156	58	32
Productive fissured	More likely	45	22	10
Sand and gravel	More likely	13	8	6
Poorly productive	Less likely	604	105	59
	Total	**818**	**193**	**107**

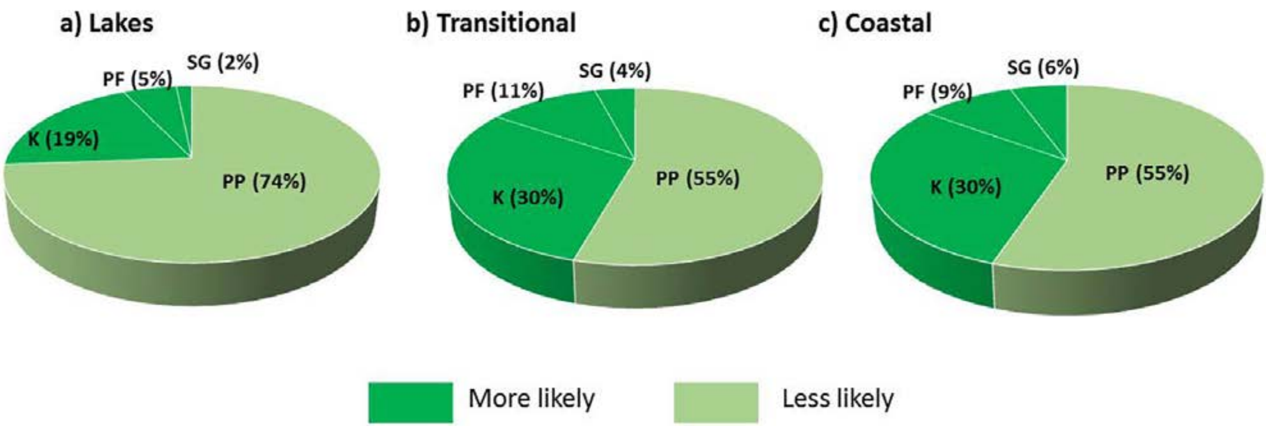

Figure 3.1. Pie chart of scale 1 "more likely" and "less likely" classification for (a) lake, (b) transitional and (c) coastal water bodies, karstic (K), productive fissured (PF), sand and gravel (SG) and poorly productive (PP) aquifer types.

Table 3.2. Set of lakes identified as turloughs and removed from the analyses

Lake name	Lake EU code	Groundwater body aquifer type
Coolcam Lough	IE_SH_26_649	Karstic
Lough Funshinagh	IE_SH_26_701	Karstic
Gortlecka Lake	IE_SH_27_102	Karstic
Lough Mannagh	IE_WE_29_168	Karstic
Coole Lough	IE_WE_29_196	Karstic
Glenamaddy Turlough	IE_WE_26_679	Karstic
Island Lake	IE_WE_34_334	Karstic with gravel
Mannin Lake	IE_WE_34_398	Karstic with gravel

On the basis of conducted and published research and the combined experience of the research team and steering committee, a number of lakes and TRAC water bodies were assigned a higher likelihood (Table 3.3). This occurred when it was observed and agreed upon that the national spatial datasets employed had failed to highlight a particular water body that is known to host groundwater discharge.

The final results clearly highlight the dominance of water bodies underlain by karst aquifers in the higher likelihood categories (Table 3.4, Figure 3.2).

The distribution of lake and TRAC water bodies by likelihood of groundwater discharge is presented in Figure 3.3.

Table 3.3. Lake and TRAC water bodies classified as "very high" likelihood on the basis of expert knowledge

Water body name	EU code	Groundwater body aquifer type	Reason
Waterford Harbour	IE_SE_100_0000	Karstic	Spring <100 m
Lough Owel	IE_SH_26_703	Karstic	Spring <100 m
Lough Key	IE_SH_26_724	Poorly productive	Spring <100 m

Table 3.4. Final national characterisation of lake and TRAC water body by likelihood category ("very high", "high", "moderate", "less" and "least") and aquifer type (K, karstic; PF, productive fissured; SG, sand and gravel; PP, poorly productive)

Water body	Groundwater body aquifer type	Very high	High	Moderate	Less	Least
Lake	K	34	64	42		
	PF	6	28	20		
	SG	3	5	3		
	PP	1			477	125
	TOTAL	**44**	**97**	**65**	**477**	**125**
Transitional	K	16	25	15		
	PF	3	16	5		
	SG	1	6	1		
	PP				71	34
	TOTAL	**20**	**47**	**21**	**71**	**34**
Coastal	K	16	8	3		
	PF	2	11			
	SG	2	6			
	PP				47	10
	TOTAL	**20**	**25**	**3**	**47**	**10**

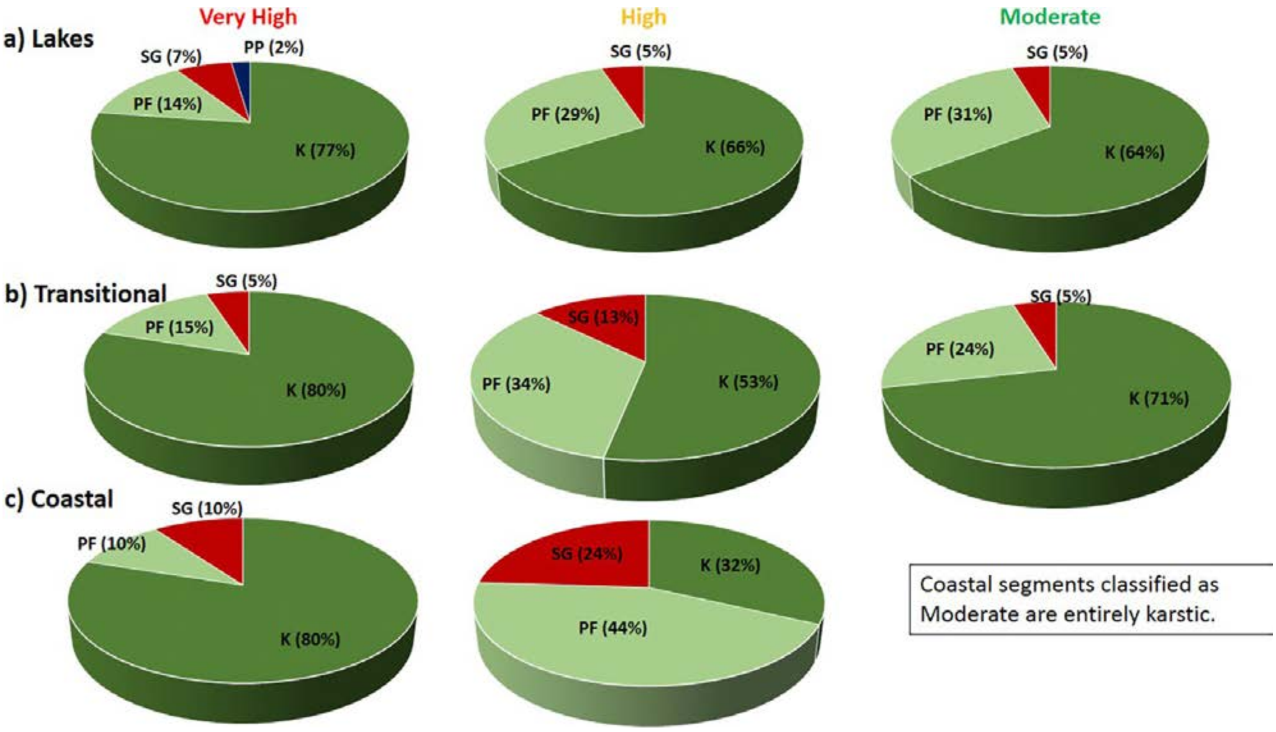

Figure 3.2. Pie chart of the final national characterisation of likelihood for groundwater discharge detailing the "very high", "high" and "moderate" likelihood for (a) lake, (b) transitional and (c) coastal water bodies by aquifer type (K, karstic; PF, productive fissured; SG, sand and gravel; and PP, poorly productive).

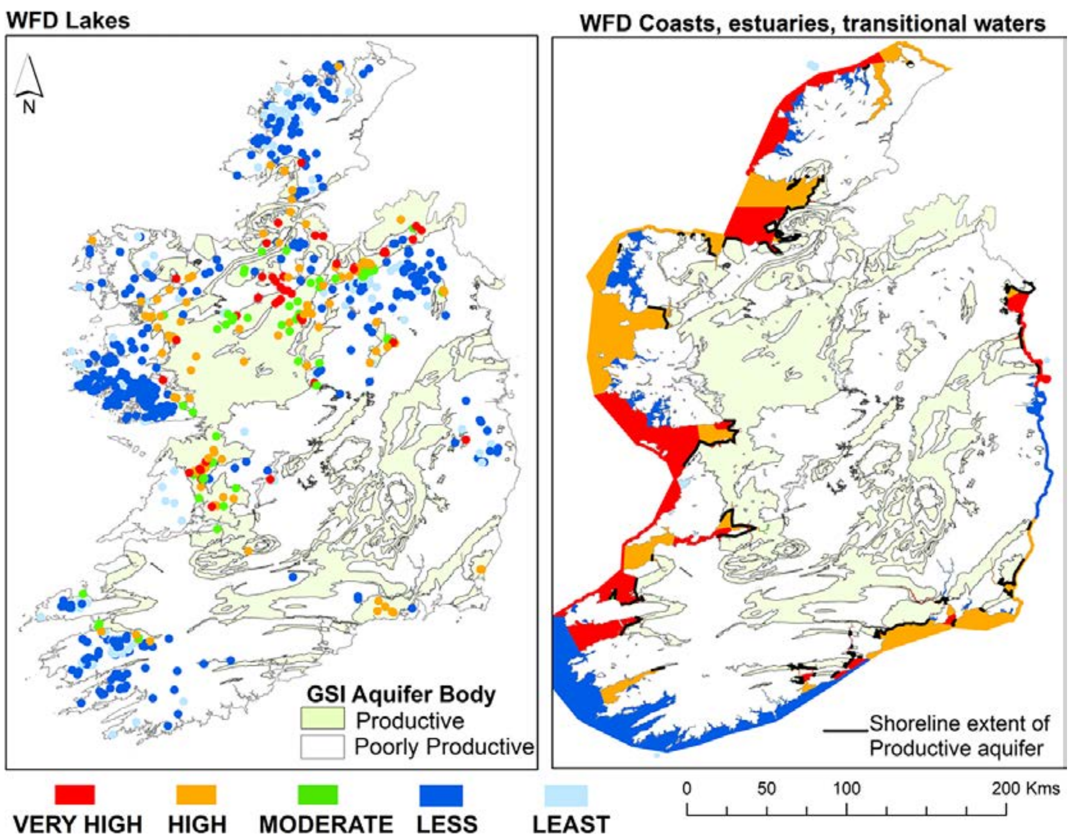

Figure 3.3. Spatial distribution of the likelihood for groundwater discharge to (left) lake and (right) TRAC water bodies nationally. Likelihood classes include "very high", "high", "moderate", "less" and "least"

3.2 National Assessment of Groundwater Discharge to Lakes and Transitional and Coastal Water Bodies using Remote Sensing

Satellite-derived temperature and standard anomaly maps were generated for a total of 122 lakes and 137 TRAC water bodies comprising 57 transitional and 80 coastal water bodies nationally. The dataset includes:

- "very high", "high" and "moderate" likelihood lakes and TRAC water bodies underlain by sand and gravel and productive fissured aquifers;
- "very high", "high" and "moderate" likelihood lakes and TRAC water bodies underlain by karst;
- "less" and "least" likelihood lakes underlain by poorly productive aquifers both intersected and not intersected by faults.

The full suite of maps generated as part of the CONNECT project are available to download from the EPA SAFER website (see Appendix 2 for details). Map number, lake or TRAC water body name, satellite sensor and date of acquisition are displayed in the header of every map. Each lake and TRAC water body is presented against the backdrop of the groundwater body aquifer type, including the EPA rivers network and the GSI's fault and springs data layer.

3.2.1 Lake temperature and temperature anomaly mapping

From the summary of results for lakes (Table 3.5) it is clear that the likelihood of groundwater discharge classification has been successful. Of 122 lakes mapped, the largest anomaly values are associated with lakes within the highest likelihood categories (lakes classified as "very high" and "high" likelihood). Moreover, the size of the anomaly decreases sequentially from the "very high", "high", "moderate", through to the "less" and "least" likelihood categories. The results suggests that we should expect to find larger (i.e. more negative) thermal anomaly values in higher likelihood over lower likelihood lakes.

The link between likelihood classification, groundwater body aquifer type and thermal anomaly, as revealed through the remote sensing, is further illustrated in the summary of results (Table 3.6).

In the "very high" category, Pollaphuca Reservoir (Figure 3.4) displays the largest negative anomaly, a lake that is characterised by both sand and gravel and poorly productive aquifer types. The lake is also characterised by a high number of surface-water inputs.

From the map of surface temperature values (Figure 3.4), two very distinct zones of cooler surface water temperatures are visible, the first (a) is close to the middle of the lake beneath a large fault line, which runs from north-east to south-west across the northern section of the lake. The second (b) is a zone to the south-west of the lake. In the absence of data, at this stage in the analysis, to quantitatively verify the cold plumes as groundwater signals, ancillary data describing the physical and environmental characteristics of the lake can be used to help interpret what *potentially* might be contributing to the observed thermal signals. A number of spatial datasets are available for both visualisation purposes and can be downloaded for free from the EPA's online Envision map viewer.[5] For example, the soils adjacent to the southern shoreline are classified as surface and groundwater gleys, which are underlain by granite till. This suggests that the soil is saturated with groundwater and therefore it is highly probable that groundwater is reaching the surface at this location and contributing to the observed thermal signal (Figure 3.5).

5 http://gis.epa.ie/Envision

Table 3.5. Summary of thermal anomaly values and total number of lakes mapped by likelihood classification

Likelihood classification	Mean negative anomaly	Maximum negative anomaly	Total no. of lakes mapped (% total)
Very high	–1.8	–3.0	19 (16)
High	–1.7	–2.5	47 (38)
Moderate	–1.5	–2.4	24 (20)
Less	–1.4	–2.0	20 (16)
Least	–1.3	–1.5	12 (10)

Table 3.6. Negative anomaly values by likelihood classification and groundwater body aquifer type, detailing lake water bodies with the largest negative anomaly values for each likelihood class

Groundwater body aquifer type	No of lakes	Average negative anomaly	Maximum anomaly	Lake water body name	Lake code
Very high					
Sand and gravel	3	–2.3	–3.0	Pollaphuca	IE_EA_09_71
Karstic	12	–1.8	–2.3	Conn	IE_WE_34_406b
Productive fissured	3	–1.4	–1.4	Emy	IE_NB_03_102
				Glaslough	IE_NB_03_79
Poorly productive	1	–1.8	–1.8	Key	IE_SH_26_724
High					
Sand and gravel	3	–1.8	2.1	An Duin	IE_SH_27_121
Karstic	26	–1.7	–2.5	Melvin	IE_NW_35_160
				Deravarragh	IE_SH_26_708
Productive fissured	18	–1.6	–2.0	Bofin	IE_SH_26_747a
Moderate					
Sand and gravel	3	–1.3	–1.6	Coosan	IE_SH_26_750c
Karstic	3	–1.5	–2.0	Errit	IE_SH_26_702
Productive fissured	19	–1.6	–2.4	Bridget	IE_SH_27_117
Less					
Poorly productive	19	–1.4	–2.0	Graney	IE_SH_25_190
				Skeagh	IE_EA_07_267
Least					
Poorly productive	13	–1.3	–1.5	Dunragh	IE_NW_37_197
				Ramor	IE_EA_07_275
				Acurry	IE_EA_07_242
				Tay	IE_EA_10_25

While Pollaphuca is underlain by a sand and gravel aquifer to the north of the lake, the majority of the lake is underlain by poorly productive aquifers. It would appear from the location of the thermal anomalies that groundwater discharge to the lake is potentially originating from the poorly productive aquifers.

Of the lakes underlain by karstic aquifers, Lough Melvin (Figure 3.6) yielded the highest anomaly value and was classified with a “high” likelihood for groundwater discharge. Two distinct plumes are visible in the surface temperature map and the map of standardised temperature anomaly reveals two large negative anomalies at the same location. In particular, the first plume (a) appears to coincide with the intersection of two faults.

Lough Conn (Figure 3.7), which was classified as “very high” likelihood, is also underlain by karst and revealed strong thermal gradients following the remote sensing analyses. The plumes also appear to be linked to the presence of two large faults, which intersect close to the lake margin and likely form the entry pathway for groundwater into the lake at this point. The lake is underlain almost entirely by karstic aquifers with poorly productive aquifers adjacent to the shoreline in the south.

The anomaly amongst the “very high” likelihood lakes is Lough Key, which was classified as “less likely” during scale 1. However, a review of the GSI’s faults and springs databases revealed the extent to which the lake is surrounded by springs and consequently the lake was awarded “very high” likelihood. Lough Key revealed strong thermal gradients following the remote sensing analyses (Figure 3.8). The lake is intersected by a large fault and is fed by streams that traverse karstic aquifers in the south, which are likely contributing to the observed remote sensing signals.

Of all of the lakes intersected by productive fissured aquifers, Lough Bridget (Figure 3.9), classified as “moderate” likelihood, displayed the strongest negative

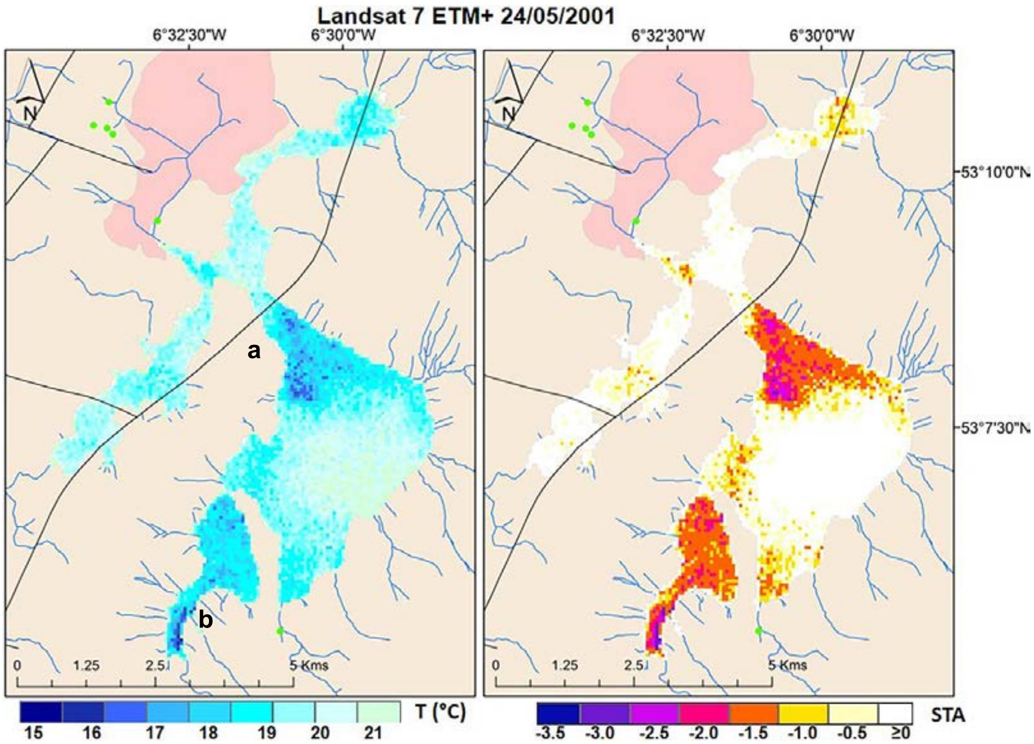

Figure 3.4. Spatial distribution of lake surface temperatures (°C) (left) and STA (right) generated from a Landsat image, acquired 24 May 2001, of Pollaphuca Reservoir, Co. Wicklow. The lake is underlain by sand and gravel (SG) and productive fissured (PF) aquifers. Spring locations are illustrated by green dots and mapped faults as solid black lines. Surface-water discharges (rivers and streams) are mapped in blue. Two distinct cold water plumes and corresponding anomalies are visible at locations a and b.

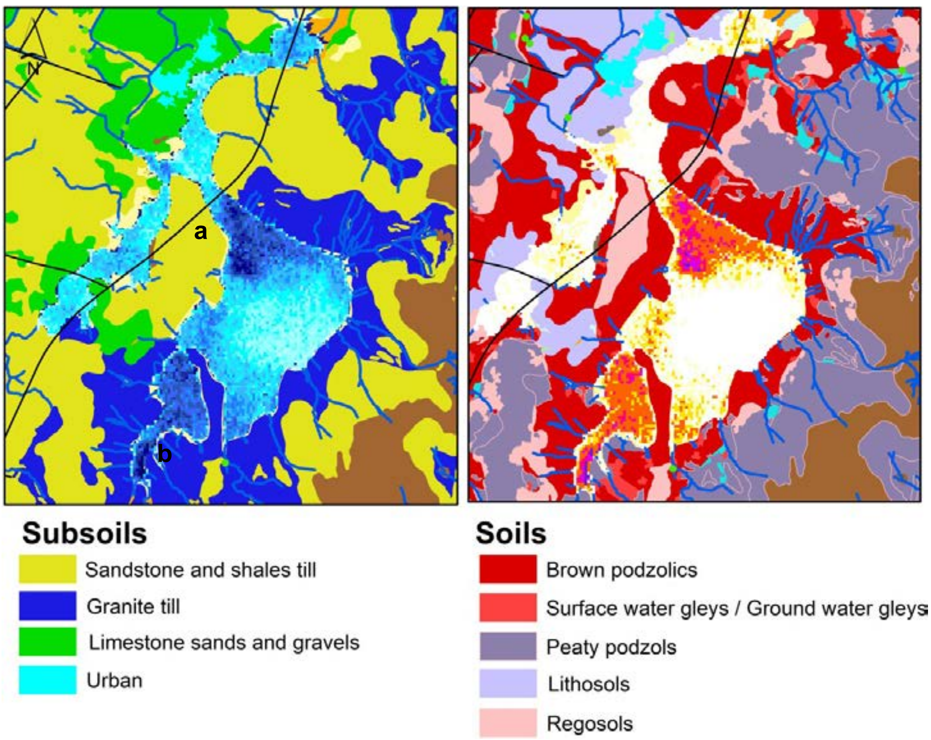

Figure 3.5. Distribution of subsoils and soils adjacent to Pollaphuca Reservoir, Co. Wicklow, relative to the location of the thermal anomalies, a and b, marked in red.

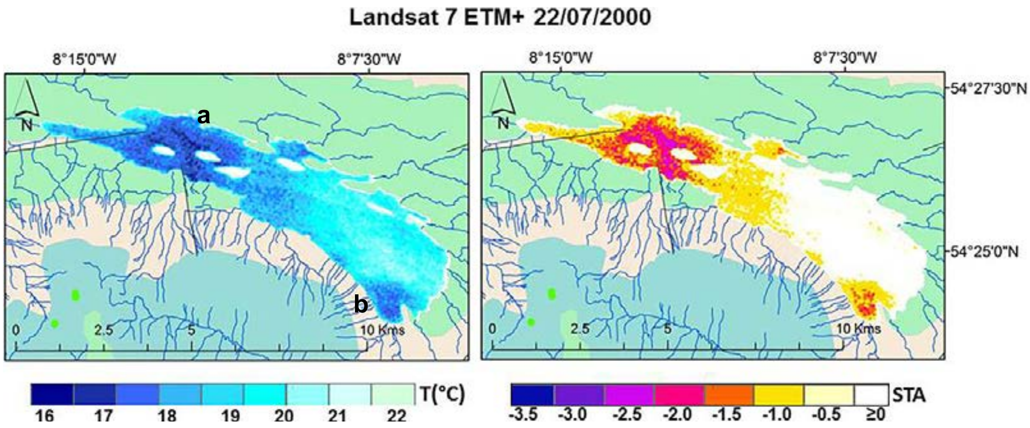

Figure 3.6. Spatial distribution of lake surface temperatures (°C) (left) and STA (right) generated from a Landsat image, acquired 22 July 2000, of Lough Melvin, Co. Leitrim. The lake is underlain by productive fissured (PF) and poorly productive (PP) aquifer types. Spring locations are illustrated by green dots and mapped faults as solid black lines. Surface-water discharges (rivers and streams) are mapped in blue. Two distinct cold water plumes and corresponding anomalies are visible at locations a and b.

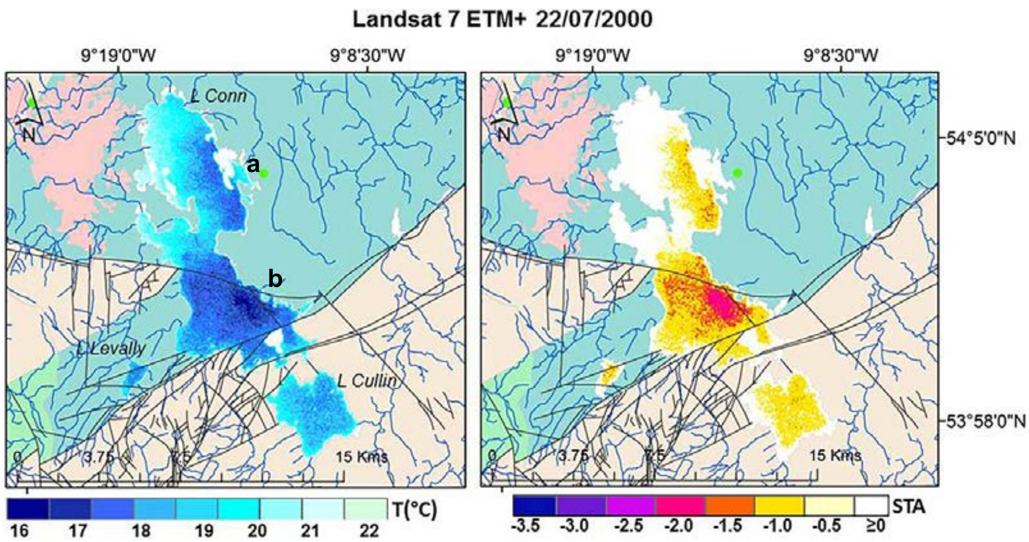

Figure 3.7. Spatial distribution of lake surface temperatures (°C) (left) and STA (right) generated from a Landsat image, acquired 22 July 2000 of Lough Conn, Co. Mayo. The lake is underlain by karstic (K) and poorly productive (PP) aquifer types. Spring locations are illustrated by green dots and mapped faults as solid black lines. Surface-water discharges (rivers and streams) are mapped in blue. Two distinct cold water plumes and corresponding anomalies are visible at locations a and b.

anomaly. Despite the relatively small surface area of the lake (approximately 0.4 km^2) a number of thermal anomalies are clearly visible across the lake surface.

A number of interesting results were obtained for lakes classified as “less” and “least” likely. Thermal plumes were visible following the remote sensing analysis of both “less” and “least” likely lakes, i.e. lakes underlain by poorly productive aquifers, which are either intersected or not intersected by faults, respectively. On average, thermal signatures were stronger across the “less likely” lakes (Table 3.5), which suggests that the GSI’s fault database is of substantial value in identifying surface-water bodies characterised by poorly productive aquifers that are most likely to be receiving groundwater inputs. Lough Graney, Co. Clare, (a “less likely” lake) exhibited the largest negative anomaly

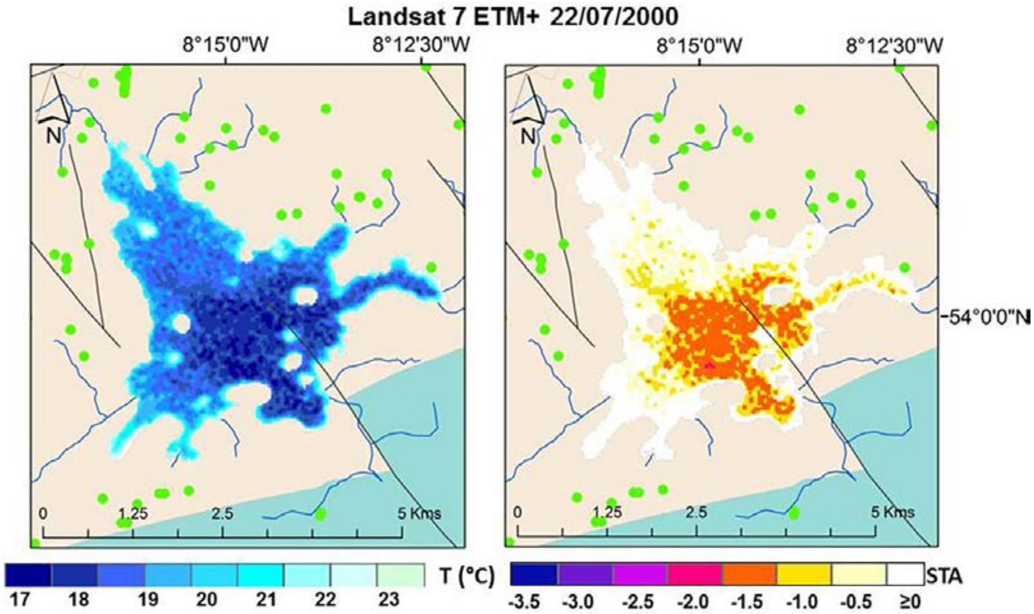

Figure 3.8. Spatial distribution of lake surface temperatures (°C) (left) and STA (right) generated from a Landsat image, acquired 22 July 2000, of Lough Key, Co. Roscommon. Spring locations are illustrated by green dots and mapped faults as solid black lines. Surface-water discharges (rivers and streams) are mapped in blue. A large and distinct cold water plume and corresponding anomaly are visible in the southern section of the lake.

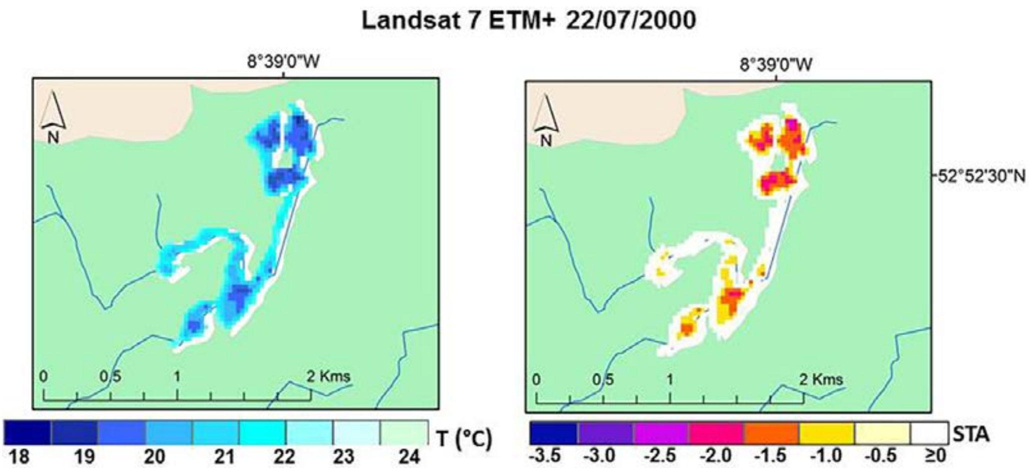

Figure 3.9. Spatial distribution of lake surface temperatures (°C) (left) and STA (right) generated from a Landsat image, acquired 22 July 2000, of Lough Bridget, Co. Clare. Surface-water discharges (rivers and streams) are mapped in blue. Plumes and corresponding anomalies are visible throughout the lake.

value of all the lakes underlain by poorly productive aquifers (Figure 3.10).

3.2.2 TRAC water body temperature and temperature anomaly mapping

A full sweep of the Irish coastline was completed using the available imagery and a total of 57 TRAC water bodies and 80 coastal water bodies were mapped. The selection of TRAC water bodies mapped was entirely subject to data availability and image resolution, and for many of the transitional water bodies, temperature gradients could not be resolved. From the summary of results (Table 3.7), however, it is clear that the GIS classification of transitional water bodies was mostly successful and large average negative anomaly values

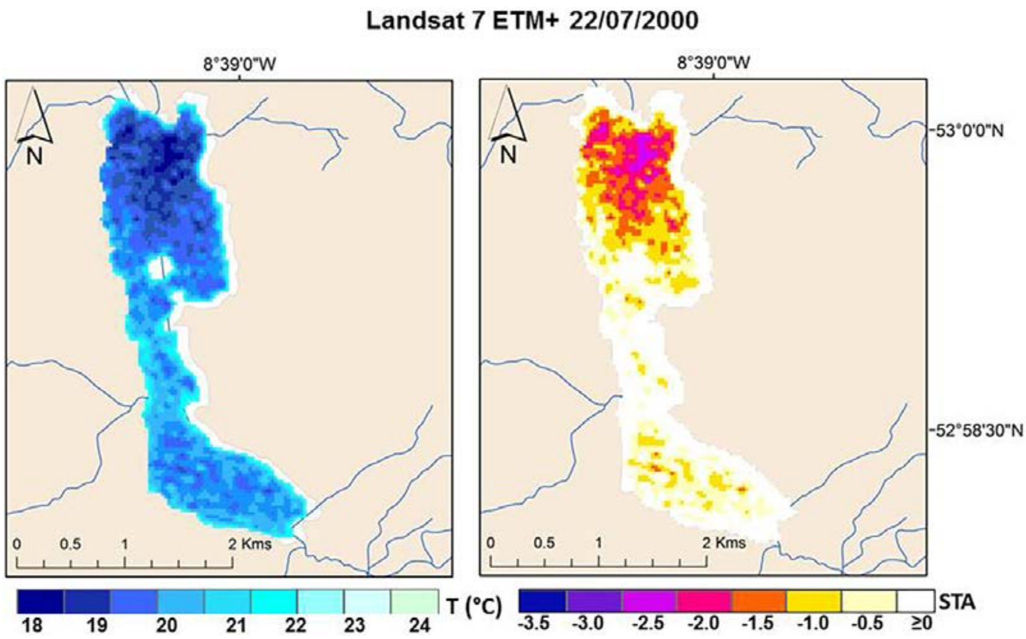

Figure 3.10. Spatial distribution of lake surface temperature (°C) (left) and STA (right) generated from a Landsat image, acquired 22 July 2000, of Lough Graney, Co. Clare. Plumes and corresponding anomalies are clearly visible in the lake to the north.

Table 3.7. Summary of thermal anomaly values and total number of transitional water bodies mapped by likelihood classification

Likelihood classification	Mean negative anomaly	Maximum negative anomaly	Total no. of transitional water bodies mapped (% total)
Very high	–0.9	–2.2	12 (21)
High	–1.0	–2.0	16 (28)
Moderate	0	0	2 (4)
Less	–0.8	–1.5	22 (39)
Least	–0.5	–0.7	5 (8)

were typically associated with the “very high” or “high” likelihood classes.

The link between likelihood classification, groundwater body aquifer type and thermal anomaly as revealed through the remote sensing of transitional water bodies is further illustrated in Table 3.8.

Amongst the transitional water bodies classified as “very high”, the largest negative anomaly was recorded within the Lower Shannon Estuary (Figure 3.11). This result is likely explained by the tide rather than potential groundwater inputs, as, in this instance, the rise of cooler coastal waters through the estuary after low tide (which peaked at approximately 10 a.m. on the morning of image acquisition, 18 July 2013) would have contributed to the cooler temperatures recorded there – particularly as the water temperatures of the Upper Shannon Estuary (adjacent to productive aquifers) by comparison are relatively warmer.

Of the “less” and “least” likelihood transitional water bodies associated with poorly productive aquifer types, average anomaly values were below –1.0. The greatest negative anomaly values were recorded at Roundstone (Figure 3.12) for the “less likely” transitional water bodies and Clonderalaw (Figure 3.11) for the “least likely”. Both of these estuaries are fed by numerous streams and thus it would be very difficult to attribute the anomalies to groundwater inputs in the absence of ground-truthing data.

In terms of groundwater body aquifer type, the largest negative anomalies were recorded in transitional water

Table 3.8. Negative anomaly values by likelihood classification and groundwater body aquifer type, detailing transitional water bodies with the largest negative anomaly values for each likelihood class

Groundwater body aquifer types	No. of water bodies	Average anomaly	Maximum anomaly	Transitional water body name	Code
Very high					
Sand and gravel	1	–0.3	–0.3	Erne	IE_NW_030_0100
Karstic	10	–1.0	–2.2	Lower Shannon	IE_SH_060_0300
Productive fissured	1	0	0	Maigue	IE_SH_060_0700
High					
Sand and gravel	4	–2.0	–2.0	Inner Dundalk Bay	IE_NB_040_0100
Karstic	7	0	0	NA	NA
Productive fissured	5	–0.4	–0.5	Upper Shannon	IE_SH_060_0800
Moderate					
Karstic	1	0	0	Drowes	IE_NW_020_0100
Productive fissured	1	0	0	Deel	IE_SH_060_0600
Less					
Poorly productive	22	–0.80	–1.5	Roundstone	IE_WE_230_0100
Least					
Poorly productive	3	–0.5	–0.7	Clonderalaw	IE_SH_060_1200

NA, not applicable.

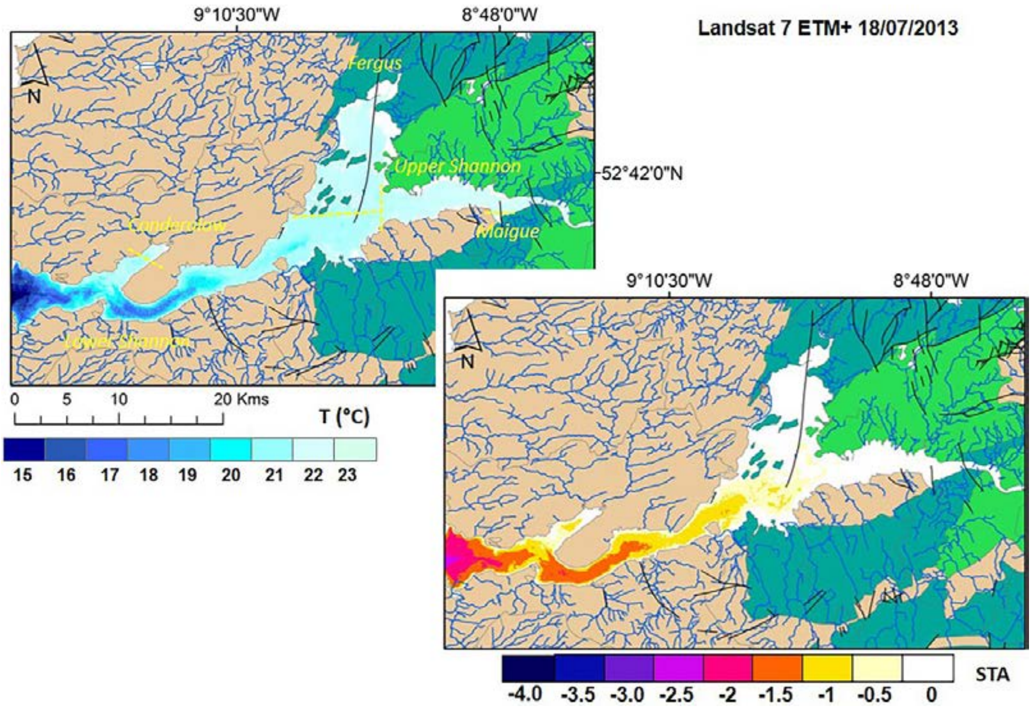

Figure 3.11. Spatial distribution of sea surface temperatures (°C) (left) and standardised temperature anomaly (right) generated from a Landsat image, acquired 18 July 2013, illustrating the lower Shannon estuary.

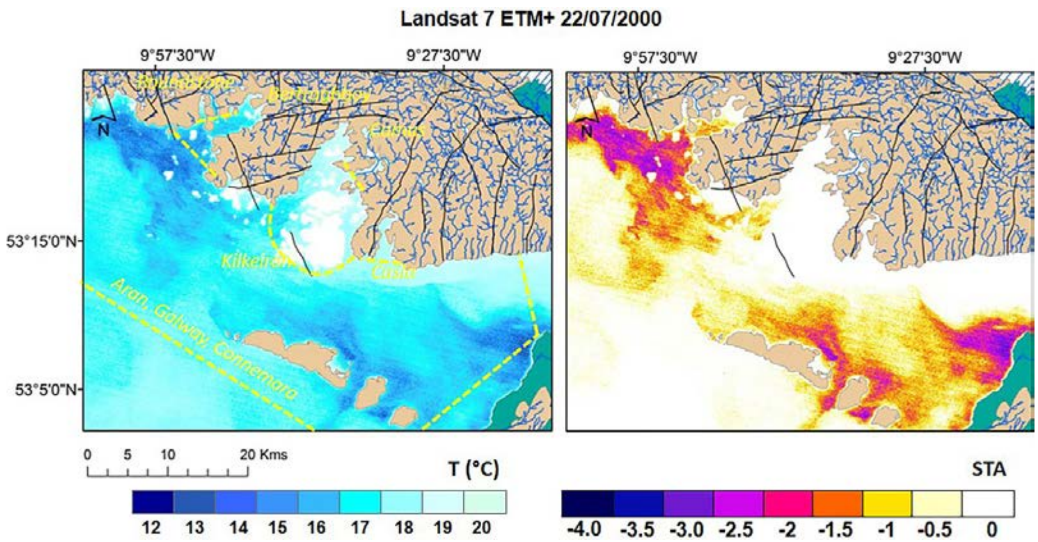

Figure 3.12. Spatial distribution of sea surface temperatures (°C) (left) and standardised temperature anomaly (right) generated from a Landsat image, acquired 22 July 2000, of north Galway Bay incorporating Roundstone Estuary.

bodies associated with karst (–2.2) followed by sand and gravel (–2.0), poorly productive (–1.5) and productive fissured (–0.5) aquifers.

From the summary of results for coastal water bodies (Table 3.9), it is clear that the GIS classification of likelihood was also successful with the “very high”, “high”, “moderate” and “less” likelihood categories producing, sequentially, the largest to smallest average negative anomaly values. However, the “least” likelihood category yielded the largest average anomaly value (–2.4) above all of the likelihood categories, as relatively large anomaly values were recorded adjacent to poorly productive coastal aquifers.

Three coastal water bodies in total comprise the “least” likelihood category, namely Doonbeg Bay (Figure 3.13), Liscannor Bay (Figure 3.13) and Fastnet waters (Figure 3.14). While cooler surface water temperatures are easily justified in the case of Fastnet waters, which are located some distance offshore, Doonbeg Bay and Liscannor Bays, with maximum anomalies of –2.1 and –3.4, respectively, can be flagged as two very unusual cases warranting further investigation.

The link between likelihood classification, groundwater body aquifer type and thermal anomaly, as revealed through the remote sensing of coastal water bodies, is further illustrated in Table 3.10. The range of negative anomaly values for coastal water bodies (from –4.2 to –1.5) is considerably large in comparison with transitional water bodies (from –2.2 to –0.3), which may be explained in part by the relatively large spatial extent of coastal water bodies and consequent development of broader temperature gradients between nearshore and offshore waters.

In terms of groundwater body aquifer type, the most negative anomalies were recorded in coastal water bodies associated with karst (–4.2) followed by poorly productive (–3.4), sand and gravel (–2.9) and productive fissured (–2.3) aquifers.

Table 3.9. Summary of thermal anomaly values and total number of coastal water bodies mapped by likelihood classification

Likelihood classification	Mean negative anomaly	Maximum negative anomaly	Total no. of transitional water bodies mapped (% total)
Very high	–2.0	–4.2	20 (25)
High	–1.8	–3.2	21 (26)
Moderate	0	0	0
Less	–1.2	–2.9	36 (45)
Least	–2.4	–3.4	3 (4)

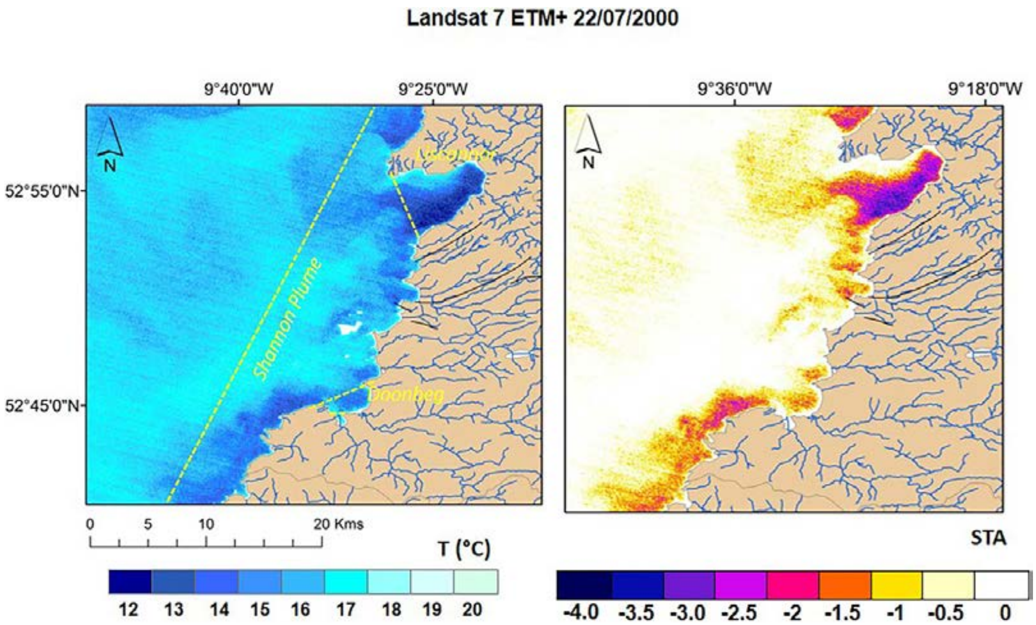

Figure 3.13. Spatial distribution of sea surface temperatures (°C) (left) and standardised temperature anomaly (right) generated from a Landsat image, acquired 22 July 2000, of Doonbeg Bay and Liscannor Bay, Co. Clare.

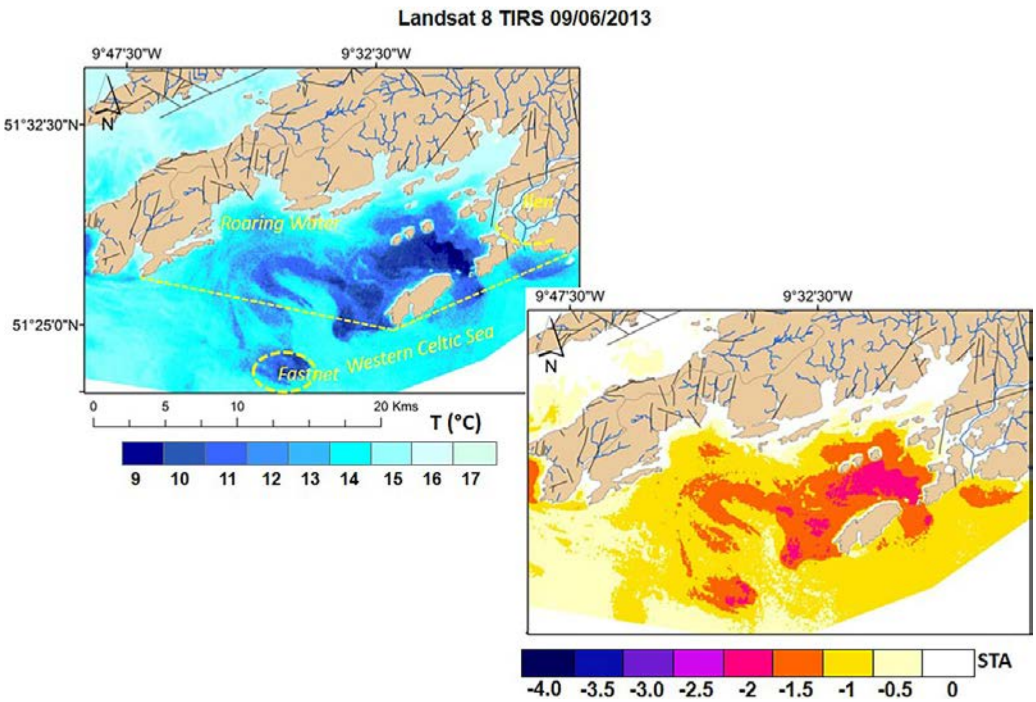

Figure 3.14. Spatial distribution of sea surface temperatures (°C) (left) and standardised temperature anomaly (right) generated from a Landsat image, acquired 9 June 2013, illustrating Fastnet waters in the south-west of Ireland.

The thermal analyses presented clearly highlight the degree to which remote sensing can inform a study seeking to localise potential groundwater inputs to lake and TRAC water bodies using satellite-derived temperature. However, conclusive statements on the presence, magnitude and significance of potential groundwater inputs cannot be made using remote sensing alone – the results must be verified and validated with support from quantitative tracers.

Table 3.10. Negative anomaly values by likelihood classification and groundwater body aquifer type, detailing coastal water bodies with the largest negative anomaly values for each likelihood class

Groundwater body aquifer types	No. of water bodies	Average anomaly	Maximum anomaly	Coastal water body name	Code
Very high					
Sand and gravel	3	–2.5	–2.9	Outer Dundalk Bay	IE_NB_040_0000
Karstic	16	–1.8	–4.2	Shannon Plume	IE_SH_070_0000
Productive fissured	1	–1.5	–1.5	North-western Irish Sea	IE_EA_020_0000
High					
Sand and gravel	3	–2.4	–2.8	Donegal Bay	IE_NW_010_0000
Karstic	8	–1.6	–3.1	Mouth of the Shannon	IE_SH_060_0000
Productive fissured	10	–1.6	–2.3	McSwynes Bay	IE_NW_080_0000
Less					
Poorly productive	36	–1.2	–2.9	South-western Atlantic seaboard	IE_SW_150_0000
Least					
Poorly productive	3	–2.4	–3.4	Liscannor Bay	IE_SH_100_0000

3.3 *In Situ* Verification and Evaluation of Groundwater Inputs using Geochemical Tracing Analyses

A summary of results from the qualitative and quantitative assessments of groundwater discharge to eight target sites is presented within this synthesis report. A full and complete presentation of results is included within the final report for this project and is available to download from the EPA SAFER archive.

3.3.1 Qualitative assessments of groundwater discharge using radon

Qualitative assessments of groundwater discharge to lakes was completed through a series of 1-day lake radon surveys. The overall results from the radon surveys (Table 3.11) confirm the presence of radon and hence groundwater in each of the lakes studied for all of the scenarios tested. The summary of radon activity values recorded during the lake surveys illustrates the variation in recorded measurements across each of the lakes and corresponding scenarios. Geology is the most important factor controlling the source and distribution of radon, and relatively high radon emissions are typically associated with particular types of bedrock and unconsolidated deposits, including granites, black shales, sedimentary limestones, permeable sandstones and metamorphic rocks (Scheib *et al*., 2013). In this study, the greatest radon activity concentrations were associated with lakes characterised by limestone, sands and gravels (e.g. Killinure) and volcanic and metamorphic rocks (e.g. Dan, Carrigavantry).

Table 3.11. Summary of lake survey data

Test scenario	Lake	^{222}Rn minimum (Bq/m^3)	^{222}Rn maximum (Bq/m^3)	^{222}Rn mean (Bq/m^3)	Mean water depth (m)	Mean water temperature (°C)	Mean air temperature (°C)
1A	Sheelin	20	152	63	2.8	9.3	11
	Gur	4	17	10	1.4	11.9	11
1B	Carrigavantry	124	324	233	1.8	5.3	7.2
	Killinure	142	1035	664	4.3	9.6	9.8
2A	Ennell	6	49	22	4	5.9	10.6
	Ramor	33	209	118	3.2	10.2	12
2B	Dan	121	1033	395	14.6	2.02	0.5
	Tay	106	201	160	19.0	2.21	1.5

Numerous radon, and hence groundwater, "hotspots" were identified. Standardised radon anomaly maps generated from the survey data clearly localise groundwater discharge zones across a number of lakes, most notably Lough Sheelin ("high" likelihood), Carrigavantry Reservoir ("high" likelihood) and Lough Ennell ("less" likelihood) (Figures 3.15–3.17).

For Lough Sheelin, the radon anomaly map (Figure 3.15) illustrates a groundwater discharge zone to the north-east, as well as two additional seepage points close to where the River Inny discharges into the lake. Further south from this location, two smaller anomalies are visible, which are adjacent to faults that intersect the lake shoreline. Standardised thermal anomaly values highlight the influx of cool water likely associated with surface-water discharges from the River Inny. The streams discharging into the lake along western and southern shorelines do not appear to affect the observed pattern of thermal or radon anomaly.

For Carrigavantry Reservoir (Figure 3.16), the radon anomaly map reveals a strong radon signal and clearly highlights sections of the western and southern shoreline of the lake as groundwater entry points. The surface area of the lake is relatively small (0.12 km^2) and the lake has no surface-water inputs. Higher resolution thermal imagery would likely better resolve temperature gradients associated with groundwater inputs into the lake.

For Lough Ennell (Figure 3.17), the radon anomaly map clearly highlights internal radon sources (springs) as well as groundwater entry points along numerous sections of the shoreline. The temperature anomaly map displays clear thermal plumes along the eastern and southern shoreline, which are likely associated with

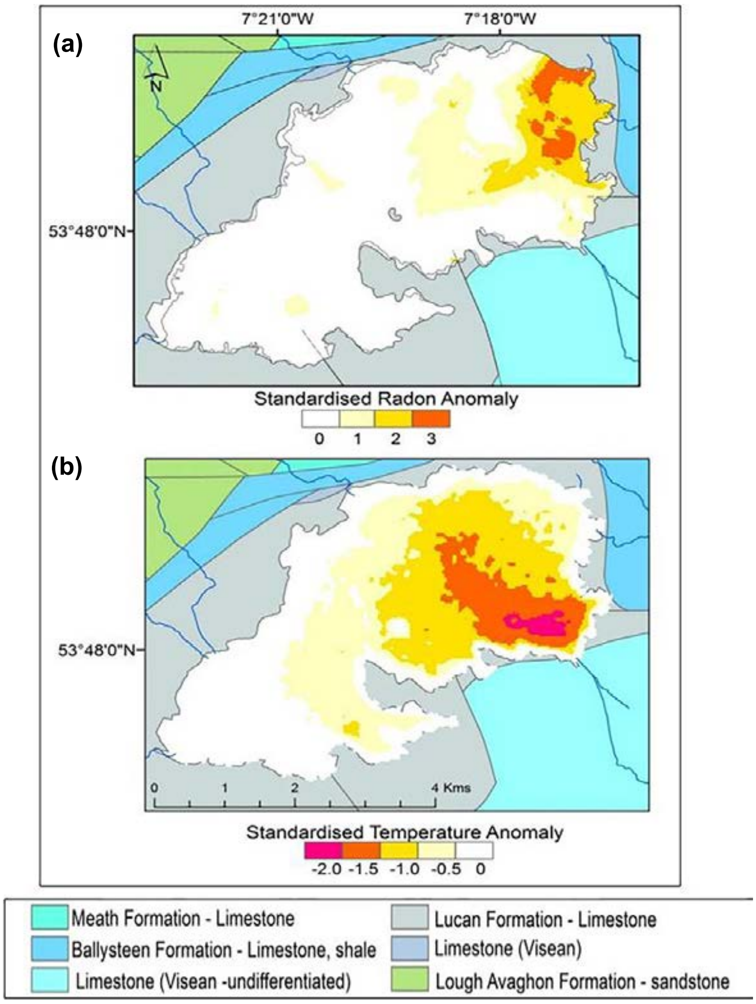

Figure 3.15. (a) Radon anomaly map of Lough Sheelin, Co. Westmeath, generated following a survey of the lake (10 April 2015). (b) Temperature anomaly map generated from a satellite image acquired 9 June 2013.

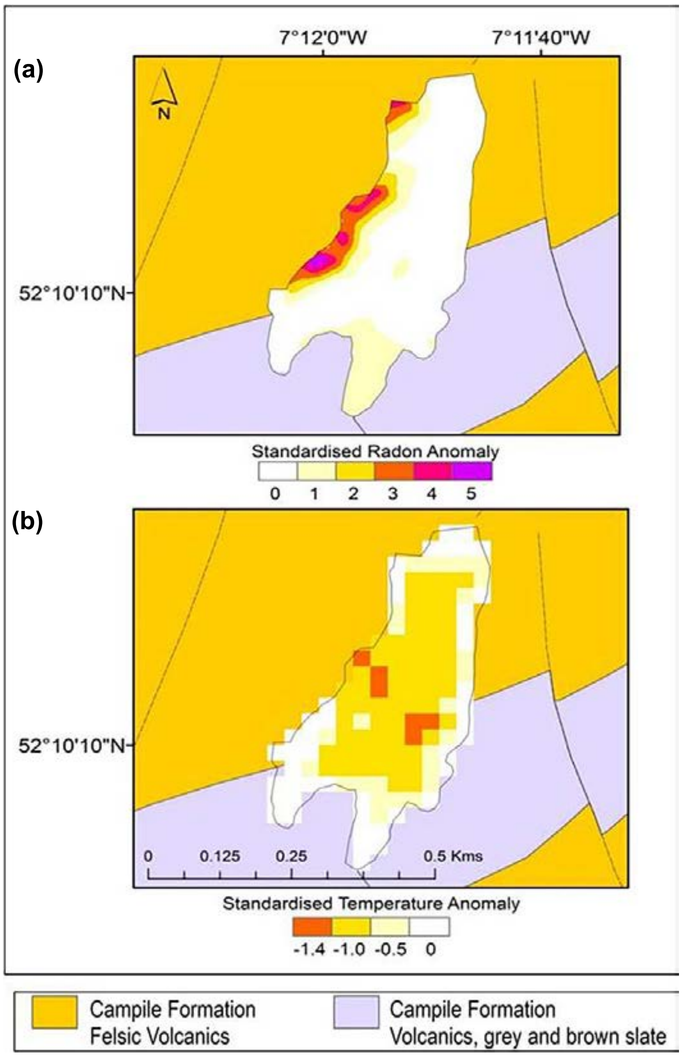

Figure 3.16. (a) Radon anomaly map of Carrigavantry Reservoir, Co. Waterford, generated following a survey of the lake (27 February 2015). (b) Temperature anomaly map generated from a satellite image acquired 28 August 1999.

groundwater-fed surface-water streams that traverse a tract of limestone before discharging into the lake from the east. The streams discharging into the lake from the east appear to have no impact on the observed pattern of thermal anomaly.

3.3.2 Quantitative assessments of groundwater discharge using radon

A radon mass balance approach (Appendix 1) was applied to quantify total groundwater discharge as the sum of pure groundwater discharging through subterranean pathways, as well as (where present) inputs from groundwater-fed surface-water inflows. The results (Table 3.12) revealed that the biggest uncertainty relates to the assignment of the appropriate groundwater end-member. Significant improvement of the radon model for quantifying groundwater discharge rates, as part of a follow-on study, can be achieved through rigorous and systematic sampling of all of the adjacent aquifers supplying each lake. Groundwater discharge rates were substantially higher for lakes with surface-water inflows, such as Loughs Sheelin, Ennell and Ramor. Water renewal times[6] were shown to vary across the lakes used in this study, but the results clearly illustrate the significance of groundwater inputs to the water budgets of Killinure (14 days), Ramor (62 days), Ennell (198 days) and Sheelin (210 days).

6 Water renewal time is defined as the time needed to replace the whole volume of a lake via total groundwater discharge and is based on the quantitative evaluations of groundwater discharge and the volume of each lake.

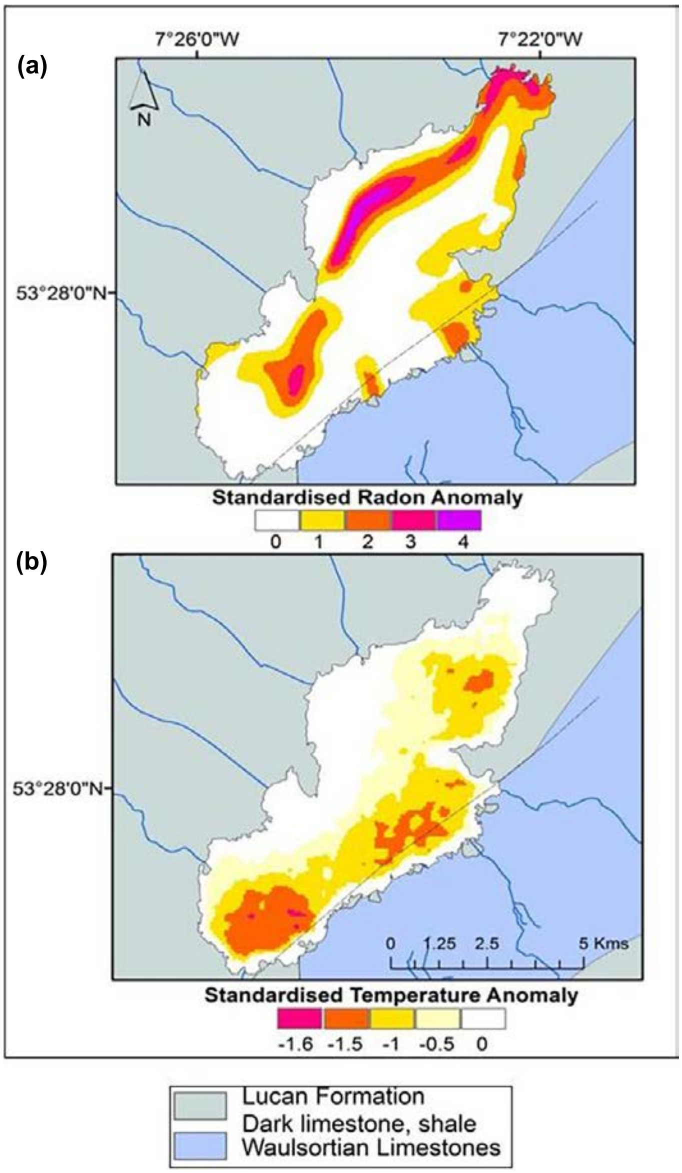

Figure 3.17. (a) Radon anomaly map of Lough Ennell, Co. Westmeath, generated following a survey of the lake (19 April 2015). (b) Temperature anomaly map generated from a satellite image acquired 18 March 2014.

Table 3.12. Summary of parameters generated to quantify total groundwater discharge rates

Test scenario	Lake	Groundwater endmember (Bq/m^3)	Atmospheric radon concentration (Bq/m^3)	Total groundwater discharge (m^3/day)	Lake volume	Water renewal time (days)
1A	Sheelin	5205	5.3	3.5×10^5	7.17×10^7	2.1×10^2
	Gur	42,321	2	7.0×10^1	1.64×10^6	240×10^2
1B	Carrigavantry	57,153	2.7	3.57×10^2	2.39×10^5	6.7×10^2
	Killinure	4735	2	7.46×10^4	1.05×10^6	0.14×10^2
2A	Ennell	620	5.3	3.7×10^5	7.36×10^7	1.98×10^2
	Ramor	11,025	5.3	3.3×10^5	2.03×10^7	0.62×10^2
2B	Dan	34,384	6.7	4.03×10^4	1.79×10^7	4.44×10^2
	Tay	34,384	6.7	9.3×10^3	1.04×10^7	11.2×10^2

3.3.3 Groundwater as a potential nutrient source

Water samples were collected during the surveys to spatially assess nutrient concentrations within the lake and, where present, in surface-water inputs to the lake. The results (Table 3.13) revealed that nutrient concentrations measured within Gur, Carrigavantry Reservoir, Dan and Tay, fell within EPA-defined water quality thresholds for nitrite, nitrate and ammonium (EPA, 2001, 2012). Loughs Sheelin, Ennell, Ramor and Killinure had ammonium concentrations in excess of EPA-defined standards for ammonium (i.e. >0.065 mg/L N). These lakes (with the exception of Killinure) also exhibited relatively high nitrate concentrations (>1.5 mg/L N), with Sheelin exhibiting the highest nitrate concentrations across all of the lakes studies, which is in breach of current EPA water quality guidelines for nitrate (>1.8 mg/L N).

It is important to note that the lakes with the highest groundwater discharge rates (Table 3.12) were those with the strongest nutrient signals. Nitrate concentrations were higher for Loughs Sheelin, Ennell and Ramor (by almost one order of magnitude) in comparison with the rest of the target lakes. In general, nutrient concentrations were higher in the samples taken from contributing rivers and streams than those from the receiving lake. This suggests that surface waters discharging into Loughs Sheelin, Ennell and Ramor are significant pollution pathways.

3.4 Summary of Output from the Geographical Information System, Remote Sensing and Geochemical Tracing Analyses

The overall goal of CONNECT was to develop tools to facilitate a national assessment of groundwater discharge to lakes and coastal areas in Ireland. A three-tiered approach was adopted to meet the objectives of this research project, which incorporated GIS, remote sensing and geochemical tracing analyses. In order to compare the results from each of the approaches, a final summary of results is presented in Table 3.14.

Table 3.13. Summary of lake nutrient measurements (nitrite, nitrate–nitrite, ammonium)

Test scenario	Lake	Nitrite (mg/L N)	Range, nitrate–nitrite (mg/L)	Range, ammonium (mg/L)
1A	Sheelin	<0.03	0.79–1.99	0.01–0.069
	Gur		0.008–0.02	0.01–0.04
1B	Carrigavantry	<0.03	0.55–0.67	0.014–0.032
	Killinure		1.0–1.12	0.021–0.076
2A	Ennell	<0.03	0.8–1.5	0.01–0.442
	Ramor		0.6–0.9	0.01–0.24
2B	Dan	<0.03	0.01–0.05	0.01–0.05
	Tay		0.007–0.022	0.037–0.042

Table 3.14. Final summary of output from the GIS likelihood classification, remote sensing of temperature anomaly and geochemical tracing analyses of groundwater discharge using radon

Test scenario	Lake	GIS likelihood classification	Maximum temperature anomaly	Maximum radon anomaly	Total groundwater discharge (m^3/day)	Water renewal time (days)
1A	Sheelin	High	–1.8	3	3.5×10^5	2.1×10^2
	Gur	High	–1.8	3	7.0×10^1	240×10^2
1B	Carrigavantry	High	–1.4	5	3.57×10^2	6.7×10^2
	Killinure	Moderate	–1.0	2	7.46×10^4	0.14×10^2
2A	Ennell	Less	–1.6	4	3.7×10^5	1.98×10^2
	Ramor	Least	–1.5	4	3.3×10^5	0.62×10^2
2B	Dan	Less	–1.2	3	4.03×10^4	4.44×10^2
	Tay	Least	–1.5	2	9.3×10^3	11.2×10^2

4 Discussion

This report outlined the development and application of cost-effective and robust GIS, remote sensing and geochemical tracing tools as part of a study seeking to detect and evaluate groundwater discharge to lake and coastal waters. The tools developed are not limited to application in Ireland and have the potential to be used elsewhere.

4.1 Geographical Information System Classification of Likelihood of Groundwater Discharge

The GIS classification of likelihood of groundwater discharge, developed as part of the CONNECT project, is a simple yet effective approach for the preliminary assessment of the potential for lake and coastal water bodies to receive groundwater inputs nationally. Using this approach, it was possible to determine which lakes and TRAC water bodies, from a very large initial dataset of over 1000 water bodies, should be prioritised for further analyses. The technique could potentially be used to help characterise river basin catchments in terms of the potential for groundwater–surface water connectivity, for example as part of second-cycle WFD river basin management planning requirements (DECLG, 2015).

However, a major limitation of the GIS approach lies in the use of the GSI's springs and faults databases, which are not complete and thus not representative nationally. Many surface-water features may have been erroneously classified as "moderate" likelihood on the basis of missing or not yet available information on the location of faults and springs in proximity to those lakes or TRAC water bodies. However, the national classification of likelihood for groundwater discharge in this report can easily be modified and updated when new information on the location of springs and faults becomes available.

4.2 National Assessment of Groundwater Discharge using Remote Sensing

As part of this study, remote sensing was used successfully to detect potential groundwater inputs by examining the thermal signature of discharging groundwater relative to surrounding water. The thermal imagery acquired must have sufficient spatial resolution to resolve temperature gradients that might reveal cold water plumes potentially linked to the inflow of groundwater, and the selection of lake and TRAC water bodies mapped was contingent not only on data availability, but also on water body size. The acquisition of satellite data for countries in northern latitudes, such as Ireland, is notoriously difficult given the amount of cloud cover, yet a substantial database of satellite imagery was acquired to meet the objectives of this research.

From the available imagery, our analyses revealed that Landsat thermal data cannot be used to adequately resolve temperature gradients across lakes and estuaries smaller than 0.5 km^2. Furthermore, because of the spatial and temporal limitations of the image dataset, we could not assume that the remote sensing analyses highlighted all of the potential seepage sites associated with each water body assessed. It is likely that higher resolution thermal surveys would further elucidate the patterns of surface water temperatures observed.

While high-resolution thermal data obtained from other systems, including aircraft sensors, drones or unmanned aerial vehicles (UAVs), for example, might further elucidate temperature differences beyond the capability of Landsat, these systems, while effective, would be prohibitively costly in terms of their use and application as part of a national assessment of groundwater discharge.

The results tell us that remote sensing of lakes and TRAC water bodies using Landsat thermal IR data derived from an archived repository can be used to highlight very important information about groundwater–surface water interactions relative to the date of image acquisition. For Lough Sheelin, for example, the significance of the River Inny as a surface-water pathway relative to the other tributaries discharging into the lake was clearly highlighted by thermal anomaly. Similarly, for Lough Ennell, the significance of the rivers draining the eastern lake catchment relative to the western lake catchment was visible in the pattern of mapped temperature. The study could be significantly strengthened through continued acquisition and processing of thermal data to facilitate seasonal analyses

of surface water temperature patterns and gain a better understanding of groundwater–surface water interactions across lakes. This was beyond the scope of the present study, but it should be noted that information derived from both repeat and seasonal temperature measurements could potentially inform any study seeking to monitor the influx and dispersion of surface water and groundwater discharges.

The results from the remote sensing were successfully used to validate the GIS classification and draw attention to the fact that larger, more anomalous, thermal plumes were mapped across lakes and TRAC water bodies associated with higher likelihood of groundwater discharge classes than the "less" and "least" likelihood classes.

4.3 *In Situ* Verification And Evaluation of Groundwater Inputs Using Geochemical Tracing Analyses

Radon activity concentration gradients were clearly detectable across each of the lakes studied and confirmed the presence of groundwater. The observed variations in the range of radon activity concentrations measured in each of the lakes was due to a number of factors, including differences in catchment geology and the presence of groundwater-fed surface-water inputs, for example. The radon surveys highlighted numerous radon "hotspots" as localised groundwater discharge zones, associated with internal sources of groundwater (i.e. springs), direct groundwater inputs from the aquifer (e.g. along lake shorelines) and indirect groundwater discharges via surface-water pathways.

The quantification of groundwater discharge is essential in terms of water resources and environmental management for evaluating the vulnerability of lakes in relation to changes in local groundwater flow patterns. Although somewhat limited in the context of the present study, the use of radon as a quantitative tracer was clearly demonstrated. Sources of radon in a lake include groundwater discharge via direct seepage from the aquifer, indirect inputs from groundwater-fed surface-water discharges, where present, and diffusion from the lake sediment. Losses of radon include radioactive decay of radon and atmospheric degassing. All sources and sinks of radon were considered as part of the radon mass balance approach used to quantify groundwater discharge rates in this study (Appendix 1). However, accurate estimation of the groundwater radon endmember was extremely difficult, particularly where it was not possible to draw groundwater samples from the aquifer within the immediate vicinity of the lake.

Radon dissolved in groundwater that is in transit may degas within large underground caves or large fissures, if present. Furthermore, radon signals within groundwater in transit may be substantiated by the addition of groundwater from other aquifers. This means that if groundwater samples are drawn from the aquifer at distances greater than 500 m from the lake shoreline, the groundwater radon endmember could potentially be over- or underestimated. During the study, it was not always possible to sample groundwater from boreholes and springs in close proximity to the lake shoreline, and in some cases (e.g. Lough Sheelin and Lough Gur) samples were drawn from reservoirs or boreholes located over 1 km from the target lake. Future studies would benefit substantially from the use of seepage meters, which can be placed in the immediate vicinity of the lake shoreline from which groundwater samples can be drawn and sampled directly from the aquifer for radon activity concentration measurements. This would hugely reduce the uncertainty of the groundwater radon endmember calculation and, consequently, the estimated groundwater discharge rates.

We acknowledge that a more rigorous approach to groundwater sampling than that used here (constrained by the scope of the present study, timeframe and budget) is necessary to ensure the complete success of the quantitative approach – by eliminating the uncertainty of the groundwater endmember estimates and subsequent calculation of groundwater discharge rates.

The study would be considerably strengthened by the use of additional groundwater tracers, such as radium, hydrogen and oxygen isotopes, which can be used to separate the contribution from direct or subterranean groundwater discharge from indirect groundwater discharge via surface-water pathways. Additional tracers are necessary for any study seeking to accurately quantify nutrient load estimates from both surface-water and groundwater sources.

The results from the remote sensing and geochemical tracing analyses in the present study clearly highlighted the success of the combined approach for use in qualitative and quantitative evaluations of groundwater–surface water interactions. For example, mapped temperature and radon anomaly highlighted

the significance of both groundwater-fed surface-water inputs and internal sources of groundwater to Lough Ennell. The fact that the patterns of temperature and radon anomaly do not correlate precisely is most likely a consequence of the unavoidable mismatch between satellite image acquisition date and the date of the radon survey. The temperature and radon data revealed different but very important information about lake system processes. Determining definitive links between the remote sensing analyses and the radon survey is difficult when using data acquired on different dates, as conditions governing lake circulation and the delivery of groundwater may be vastly different between the satellite image acquisition and radon survey dates. This affects not only the observations but the ability to draw conclusive statements as to the observed differences between the measurements.

Future work should ideally reconcile the temporal scale of the remote sensing and geochemical tracing approaches by ensuring concurrent acquisition of the thermal and radon data. This can be achieved by using UAVs or drones to capture thermal data at the same time as the radon survey, which would allow statistically robust links between groundwater discharge rates (calculated using radon mass balance) and the spatial distribution of the observed thermal anomalies to be determined. Moreover, further work is necessary to quantitatively separate the pure groundwater discharges (i.e. groundwater entering the lake via subterranean pathways) from the surface water groundwater discharges (i.e. groundwater entering the lake from groundwater-fed rivers and streams) and their associated nutrient loads in order to more precisely attribute nutrient sources and to provide more accurate estimates of nutrient load from groundwater- and non-groundwater-derived surface-water sources.

5 Final Comments

Following completion of the CONNECT research project, a number of actions are recommended:

- The acquisition and processing of remotely sensed thermal imagery that can resolve temperature gradients across lakes and TRAC water bodies should continue to identify potential groundwater seepage sites and better understand lake system and estuarine processes.
- Using the data specified in the point above, a time series dataset of lake and sea surface temperature values should be created and used to potentially inform studies seeking to evaluate the impact of climate change on lake and marine environments, for example.
- Using the present study as a baseline, further, more detailed, *in situ* studies incorporating both lakes and TRAC water bodies could be undertaken for water bodies identified as "at risk" of failing to reach WFD water quality standards as part of a fully quantitative analysis of groundwater discharge and nutrient load estimates. These studies should use additional tracers, including radium, oxygen and hydrogen isotopes, which can be used to separate direct or pure groundwater discharge via subterranean pathways from indirect groundwater entering the lake via surface-water pathways. Use of additional tracers will also allow nutrient sources to be appropriately attributed.

Our research showed that indirect groundwater discharge originating from surface-water discharges comprises a major component of the water balance of some of the lakes studied, in particular Loughs Ennell, Ramor and Sheelin. Our research also revealed that nutrient concentrations in general were higher in samples drawn from surface-water discharges to target lakes than in those drawn from the lake water body. This is important, since the quality of groundwater inputs to discharging rivers and streams will significantly impact the surface-water quality within the receiving lake. While inputs of high-quality groundwater can dilute poor-quality surface water, inputs of poor-quality groundwater will reduce surface-water quality and ecosystem health. This is particularly pertinent for lakes during periods of low surface-water flow, when both water flow and lake levels are sustained mainly through groundwater discharge.

However, groundwater exchange between an aquifer and a lake will exhibit high temporal variability and spatial heterogeneity on both regional and local scales. Moreover, the discharge of groundwater-derived nutrients to lakes and surface-water streams discharging to lakes is controlled not only by highly variable nutrient sources, but also by complex biogeochemical processes that are occurring as nutrients are transported through the aquifer to receiving surface waters.

In a recent report on national water quality (EPA, 2015), the quality of our national groundwater resources has been described as very good relative to other countries in Europe based on the proportion of groundwater bodies at poor chemical status. The European Environment Agency report on water quality for the period from 2004 to 2009 cites excessive levels of nitrate from agricultural sources as the most frequent cause of poor groundwater status across Europe (EEA, 2013). In Ireland, tests for assessing the chemical status of groundwater include, among other things, exceedances of a range of quality standards and thresholds that would result in failure to achieve the environmental objectives of associated surface waters, groundwater-dependent terrestrial ecosystems or drinking water protected areas. Following a groundwater status update in December 2014 (EPA, 2015), a very small percentage (1.7%) of groundwater water bodies were classed as poor status.

Evaluating groundwater as a source of nutrients to lake and TRAC water bodies requires knowledge of the sources of groundwater nutrient contamination, as well as the physical flows linking aquifers to surface waters and associated nutrient transport pathways and the geochemical processes occurring along these pathways that control the absolute nutrient fluxes to surface waters (Crow and Meek, 2009). The influence of nutrient loading from direct and indirect groundwater discharge is generally not well understood, yet recognising and managing the contribution of groundwater is essential for developing effective nutrient management strategies.

Our research illustrates the success of the use of natural environmental tracers, including temperature (satellite derived) and radon (^{222}Rn), to qualitatively and quantitatively assess groundwater discharge to lakes. Evaluating the potential occurrence and understanding where groundwater discharge occurs is the first step towards more in-depth geochemical surveys that seek to clarify the role played by groundwater in lacustrine or nearshore biogeochemical budgets.

While a radon mass balance was used to successfully derive estimates of total groundwater discharge, it was beyond the scope of the current project to develop further additional geochemical tracing tools to quantitatively separate direct from indirect groundwater discharges and their associated nutrient loads. This is a significant next step and future research should be undertaken to properly attribute groundwater nutrient sources.

Research completed as part of the CONNECT project has endeavoured to address key knowledge gaps in field-based scientific information on groundwater–lake activity. The outputs presented in this report could potentially be used to inform and guide any future study seeking to localise and quantify groundwater discharge and associated nutrient loading to surface-water features. This is especially important in the light of the second-cycle WFD requirements, which include the development of environmental objectives, catchment characterisation, river basin management planning and associated POMs, to gather better information and expand our knowledge of the aquatic environment.

6 References

Anderson, D.M., 2009. Approaches to monitoring, control and management of harmful algal blooms (HABs). *Ocean and Coastal Management* 52**:** 342–347.

Anderson, M.P., 2005. Heat as a groundwater tracer. *Groundwater* 43: 951–968.

Brodie, R., Sundaram, B., Tottenham, R. *et al*., 2007. *An overview of tools for assessing groundwater-surface water connectivity*. Bureau of Rural Sciences, Canberra.

Campbell, J.B. and Wynne, R.H., 2012. *Introduction to Remote Sensing*, 5th edn. Guilford Publications, New York.

Crow, A.S. and Meek, G.A., 2009. Groundwater conditions beneath beaches of Lake Huron, Ontario, Canada. *Aquatic Ecosystems Health and Management* 12: 444–455.

Daly, D., 2009. Groundwater—the 'hidden resource'. *Biology and Environment: Proceedings of the Royal Irish Academy* 109B: 221–236.

Daly, D., Archbold, M. and Deakin, J., 2014. Water framework implementation and integrated catchment management. Where are we now? Where are we going? An EPA view. Proceedings of the National Hydrology Conference, 11 November 2014, Tullamore Court Hotel, Tullamore, Co. Offaly, Ireland.

DECLG (Department of the Environment, Community and Local Government), 2015. Public Consultation Document: Significant Water Management Issues in Ireland. Department of Environment, Community and Local Government, Dublin.

Duarte, T.K., Hemond, H.F., Frankel, D. *et al*., 2006 Assessment of submarine groundwater discharge by handheld aerial infrared imagery: case study of Kaloko fishpond and bay, Hawai'i. *Limnology and Oceanography: Methods* 4: 227–236.

DURRIDGE, 2012. RAD7 Radon Detector User Manual. DURRIDGE Company Inc., Boston, MA.

EC (European Commission), 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Communities L327, Vol. 43, 22 December 2000.

EC (European Commission), 2012. The Blueprint to Safeguard Europe's Water Resources. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions (COM (2012) 673).

EEA (European Environment Agency), 2013. Chemical status indicators for water across Europe. Available online: http://www.eea.europa.eu/data-and-maps/indicators/wfd-indicator-chemical-status/assessment (accessed 15 December 2015).

EPA (Environmental Protection Agency), 2001. *Parameters of Water Quality: Interpretations and Standards*. EPA, Johnstown Castle, Wexford.

EPA (Environmental Protection Agency), 2006. *Ireland Water Framework Directive Monitoring Programme*. EPA, Johnstown Castle, Wexford.

EPA (Environmental Protection Agency), 2012. *Integrated Water Quality Report – South East Ireland*. EPA, Johnstown Castle, Wexford.

EPA (Environmental Protection Agency), 2015. *Water Quality in Ireland 2010–2012*. EPA, Johnstown Castle, Wexford.

Hunter-Williams, N., Misstear, B., Daly, D. *et al*., 2011. National groundwater recharge map for Ireland. 31st Annual Groundwater Conference, International Association of Hydrogeologists (IAH) Irish Group, Tullamore, Co. Offaly, 12–13 April 2011.

Kelly, J.L., Glenn, C.R. and Lucey, P., 2013. High resolution aerial infrared mapping of groundwater discharge to the coastal ocean. *Limnology and Oceanography: Methods* 11: 262–277.

Lewandowski, J., Meinikmann, K., Ruhtz, T. *et al*., 2013. Localisation of lacustrine groundwater discharge (LGD) by airborne measurement of thermal infrared radiation. *Remote Sensing of Environment* 138: 119–125.

Moe, H., Craig, M. and Daly, D., 2012. *Poorly Productive Aquifers – Monitoring Installations and Conceptual Understanding*. Environmental Protection Agency, Johnstown Castle, Wexford.

Paerl, H.W., 1997. Coastal eutrophication and harmful algal blooms: importance of atmospheric deposition and groundwater as "new" nitrogen and other nutrient sources. *Limnology and Oceanography* 45: 1154–1165.

Robinson, C., 2015. Review on groundwater as a source of nutrients to the Great Lakes and their tributaries. *Journal of Great Lakes Research*, 41: 941–950.

Scheib, C., Appleton, J.D., Miles, J.C.H. *et al*., 2013. Geological control on radon potential in England. *Proceedings of the Geologist's Association*, 124: 910–928.

Schuetz, T. and Weiler, M., 2011. Quantification of localised groundwater inflow into streams using ground-based infrared thermography. *Geophysical Research Letters* 38: L03401.

Shaw, G.D., White, E.S. and Gammons, C.H., 2013. Characterising groundwater–lake interactions and its impact on lake water quality. *Journal of Hydrology* 492: 69–78.

Slomp, C.P. and Van Cappellen, P., 2004. Nutrient inputs to the coastal ocean through submarine groundwater discharge: controls and potential impact. *Journal of Hydrology* 295**:** 64–86.

USGS (United States Geological Survey), 2014. USGS GLOVIS Earth Resources Observation and Science Centre (EROS) satellite data. Available online: http://glovis.usgs.gov/ (accessed 11 May 2014).

Williams, J., 2012. Catchment management – setting the scene. *Water Journal* 39: 94–98.

Wilson, J. and Rocha, C., 2012. Regional scale assessment of Submarine Groundwater Discharge in Ireland combining medium resolution thermal imagery and geochemical tracing techniques. *Remote Sensing of Environment* 119: 21–34.

Wilson, J. and Rocha, C., 2016. A combined remote sensing and multi-tracer approach for localising and assessing groundwater–lake interactions. *Journal of Applied Earth Observation and Geoinformation* 44: 195–204.

Winter, T.C., Harvey, J.W., Franke, O.L. *et al*., 1998. *Ground and surface water a single resource*. US Geological Survey Circular 1139, USGS, Denver, CO.

Zhu, C. and Schwartz, F.W., 2011. Hydrogeochemical processes and controls on water quality and water management. *Elements* 7: 169–174.

Units, Acronyms and Abbreviations

Bq/m³	Becquerels per cubic metre
EPA	Environmental Protection Agency
ETM+	Enhanced Thematic Mapper plus
EU	European Union
GIS	Geographical information system
GLOVIS	Global Visualisation Viewer
GPS	Global positioning system
GSI	Geological Survey of Ireland
ICM	Integrated catchment management
IR	Infrared
K	Karstic
mg/L	Milligrams per litre
m/s	Metres per second
m³/day	Cubic metres per day
POM	Programme of measures
PF	Productive fissured
PP	Poorly productive
RBMP	River basin management plan
^{222}Rn	Radon-222
SG	Sand and gravel
SRA	Standardised radon anomaly
STA	Standardised temperature anomaly
TIRS	Thermal Infrared Sensor
TRAC	Transitional and coastal
UAV	Unmanned aerial vehicles
USGS	United States Geological Survey
WFD	Water Framework Directive
WRS	World Reference System

Appendix 1

A1: Quantitative Assessments of Groundwater Discharge: The Radon Mass Balance

The assessment of groundwater discharge rates into lakes using radon as a tracer is based on a mass balance approach, which entails: (1) the quantitative identification of all radon sources and sinks in the system studied; (2) the measurement of the excess radon inventory, i.e. the radon inventory that is not supported by the decay of radium in a water column representative of the lake water body (under the consideration of homogeneous groundwater discharge through the lake bottom and a well-mixed lake water body); (3) the determination of the total radon input flux into the lake needed to balance that excess radon inventory; and (4) the calculation of the groundwater component of the total radon input flux, which can be converted into a groundwater flux using the radon concentration of the groundwater end-member (Schmidt *et al.*, 2010).

The radon mass balance approach is based on a number of assumptions. Firstly, it is assumed that the lake waters are well mixed horizontally and vertically, secondly, that radon sources include diffusion from sediments and groundwater discharge and, thirdly, that losses of radon include atmospheric evasion (degassing) and radioactive decay. Radon losses in lakes via recharge to the aquifer are considered minor because the concentration of radon seeping into sediments is generally much lower than the concentration of radon seeping into the lake (Dimova and Burnett, 2011).

In this study, the radon budget for lakes is the balance between total inflows via groundwater (F_{Total} as the sum of the advective groundwater inputs delivered through the subterranean pathway or from surface-water pathways via groundwater-fed rivers and streams) and losses solely by atmospheric degassing and radon decay.

Under steady-state conditions, the sum of radon sources equals the sum of radon sinks and the *radon mass balance model* for a lake can be set up as follows (equation A1.1):

$$F_{Total} + F_{Diff} + \lambda_{Rn} I_{Ra} = \lambda_{Rn} I_{Rn} + F_{Atm} \qquad (A1.1)$$

where:

F_{Total} is total groundwater input into the lake;

F_{Diff} is the input of radon from sediment diffusion;

λ_{Rn} is the decay constant of radon;

I_{Ra} is the ^{226}Ra inventory [radium concentration × water depth (it is assumed that ^{226}Ra and radon are in secular decay equilibrium)];

I_{Rn} is the radon inventory in the water column (radon concentration × water depth); and

F_{Atm} is radon loss through atmospheric degassing.

As lake water lacks major contact with radon-emanating material within the aquifer, background concentrations of ^{226}Ra in lakes are considered negligible and the $\lambda_{Rn} I_{Ra}$ term can be omitted from the mass balance (Schmidt *et al.*, 2010). It is also important to note that any radium that may present will be sequestered by solids in waters with low salinities and will not be released into the water column of freshwater bodies as a consequence.

Radon degassing across the air–water interface causes significant radon loss (atmospheric loss) from surface-water bodies. The rate of radon loss depends on the intensity of the turbulent gas transfer and on the concentration gradient at the air–water interface causing molecular diffusion, and is estimated as follows (equation A1.2; Macintyre *et al.*, 1995):

$$F_{Atm} = k(C_w - \alpha C_{air}) \qquad (A1.2)$$

where C_w and C_{air} are the radon concentrations in water and air (Bq/m^3), respectively; α (dimensionless) is the partition coefficient of radon between water and air determined from the Fritz–Weigel equation (Weigel, 1978) (equation A1.3):

$$C_w = C_{air} \times (0.105 + 0.405e^{-0.0502T}) \qquad (A1.3)$$

where T is air temperature (°C); and k is the radon transfer velocity (cm/h). The radon transfer velocity (k) is governed by wind speed and water currents and is calculated using an empirical equation valid for lakes (Macintyre *et al.*, 1995) (equation A1.4).

$$k_{600} = 0.45\left(u_{10}\right)1.6\left(\frac{\text{ScRn}}{600}\right)^{-\frac{2}{3} or -\frac{1}{2}} \qquad (A1.4)$$

The term 600 represents a standardisation, u_{10} represents the wind speed 10 m above the water surface (m/s), ScRn represents the dimensionless "Schmidt number" of radon (the ratio of the kinematic viscosity of water and the radon molecular diffusion coefficient in water derived from Liss and Merlivat (1986) to the power of –2/3 or –1/2 where wind speeds are less than or greater than 3 m/s, respectively.

In order to satisfy the radon mass balance given in equation A1.1, the radon sink terms $\lambda_{Rn}I_{Rn}$ and F_{Atm} must quantitatively correspond to the radon source terms F_{Diff} and F_{Total}. Assuming steady-state conditions, the excess radon remaining in the system after all known sources and sinks have been calculated, is accounted for by the remaining unknown term, F_{Total}. By dividing the estimated groundwater radon flux (F_{Total}) by the radon activity of the groundwater endmember, total groundwater discharge rate can be determined.

References

Dimova, N.T. and Burnett, W.C., 2011. Evaluation of groundwater discharge into small lakes based on the temporal distribution of radon-222. *Limnology and Oceanography* 56: 486–494.

Liss, P.S., and Merlivat L., 1986. Air–sea gas exchange rates: introduction and synthesis. In Baut-Medard, P. (ed.) *The Role of Air–Sea Exchange in Geochemical Cycling*. Springer, New York, pp. 113–127.

Macintyre, S, Wanninkhof, R. and Chanton, J.P., 1995. Trace gas exchange across the air–water interface in freshwaters and coastal marine environments. In Matson, P.A. and Harriss, R.C (eds), *Biogenic trace gases: Measuring emissions from soil and water*. Blackwell, Oxford, UK, pp. 52–97.

Schmidt, A., Gibson, J.J., Santos, I.R. *et al*., 2010. The contribution of groundwater discharge to the overall water budget of two typical Boreal lakes in Alberta/Canada estimated from a radon mass balance. *Hydrology and Earth Systems Science* 14: 79–89.

Weigel, F., 1978. Radon. *Chemiker Zeitung* 102: 282.

Appendix 2

The satellite-derived surface water temperature and temperature anomaly maps generated as part the CONNECT project are available to download from the EPA SAFER website at the following URL: http://erc.epa.ie/safer/iso19115/displayISO19115.jsp?isoID=3085.

For the lakes, please go to **Attachment 20** (WP2_Results_ThermalMaps_Lakes_FINAL.pptx).

For the TRAC water bodies, please go to **Attachment 17** (WP2_Results_ThermalMaps_TRACs_FINAL.pptx).

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL

Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú

Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:

- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha);*
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce

- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol

- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn

- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil

- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta

- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas

- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol (*m.sh. Timpeall an Tí, léarscáileanna radóin).*
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta

- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:

- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- An Oifig um Cosaint Raideolaíoch
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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Combining earth observation and geochemical tracing techniques for groundwater detection and evaluation in Ireland

epa Research
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Author: Jean Wilson, Carlos Rocha and Catherine Coxon

Identifying pressures

Nearly all surface water features interact with groundwater which means that pollution of surface-water features can cause deterioration in groundwater quality and conversely, contamination of groundwater can degrade surface water systems. Groundwater-surface water interactions therefore may significantly impact water chemistry, water quality, biology and ecology and recent studies identify groundwater inputs as one of the main drivers of eutrophication in lakes and a precursor to algal blooms in coastal areas. Despite acknowledgement of its potential impact, groundwater discharge to surface-water features remains a poorly-understood process particularly when implementing water monitoring and management programmes in Ireland and elsewhere. This is because groundwater discharge is highly variable, both spatially and temporally, and identifying where and how much groundwater discharge is occurring is an extremely challenging task. In recognition of this knowledge gap and the implications for water management practices, the overall goal of CONNECT was to develop tools to facilitate a national assessment of groundwater discharge to lake and coastal waters in Ireland.

Informing Policy

Groundwater discharge is a potentially significant source and pathway of freshwater and nutrients to lakes and coastal areas with implications for the type and extent of monitoring required to fulfil national and international environmental policy objectives such as those defined as part of the EPA's Integrated Catchment Management (ICM) strategy to achieving second cycle Water Framework Directive targets. ICM necessitates a holistic and integrated approach to the management of land, biodiversity, water and community resources at the catchment scale which requires (in part) catchments to be viewed in three dimensions to facilitate a full and complete under-standing of where water comes from and how it moves above, below and through the landscape. This calls for the development of efficient tools to evaluate groundwater-surface water interactions in order to better understand and account for knowledge of the sources and pathways of groundwater discharge to lakes and coastal areas.

Developing Solutions

Research completed as part of the CONNECT project endeavoured to address knowledge gaps in field-based scientific information on the interaction between groundwater, lakes and coastal areas. GIS, remote sensing and geochemical tracing tools were developed and combined to detect and evaluate groundwater-surface water interactions. The outputs presented in this report can be used potentially to inform and guide any future studies seeking to localise and quantify groundwater discharge and associated nutrient loading to surface-water features.

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